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Abstract

This paper clarifies the role and the impact of foreign exchange dealers in the relationship between foreign exchange intervention and nominal exchange rates using a unique dataset that disaggregates trades by dealer and by type of trade. The paper tests a number of market microstructure hypotheses. Results suggest that central bank orders and other customer orders are treated similarly by dealers who are engaged in short-run speculative and risk-sharing-motivated interdealer trading. While private payoff-relevant information is contained in trades, speculative interdealer trading is based only on transitory non-payoff-relevant information. A central bank considering intervention must consider both the signal it wishes to convey to the market and the subsequent trading strategies utilized by dealers.

JEL classification: F31, G14, G21
Bank classification: Exchange rates; Financial institutions; Financial markets

Résumé

Dans cette étude, l'auteur clarifie le rôle que jouent les cambistes dans la relation entre les interventions sur le marché des changes et les taux de change nominaux. Pour ce faire, il recourt à un ensemble unique de données sur les opérations, décomposées par cambiste et par type de client. Il vérifie également un certain nombre d'hypothèses relatives à la microstructure du marché. D'après les résultats qu'il obtient, les ordres émanant de la banque centrale et des autres clients sont traités de la même façon par les cambistes qui concluent avec d'autres cambistes des opérations spéculatives à court terme, motivées par le partage des risques. S'il est vrai que les opérations intègrent des informations privilégiées liées à la valeur anticipée des actifs, celles que les cambistes mènent à des fins spéculatives, pour leur part, se fondent uniquement sur des informations transitoires non liées à la valeur anticipée. Une banque centrale qui envisage de procéder à une intervention doit tenir compte tant du signal qu'elle souhaite transmettre au marché que des stratégies ultérieures adoptées par les cambistes.

Classification JEL : F31, G14, G21
Classification de la Banque : Taux de change; Institutions financières; Marchés financiers

1. Introduction

While most theoretical studies suggest that central bank intervention can potentially influence both the level and the variance of the nominal exchange rate,[1] empirical evidence[2] indicates that such intervention does not usually have the desired impact. This problem is linked to the fact that exchange rate dynamics are not well understood. A natural starting point in any study of the effect of intervention operations on the nominal exchange rate is the formulation of a model of the exchange rate that correctly predicts or explains dynamics in the foreign exchange (FX) market. In macroeconomic models of the exchange rate, variables such as interest rates, money supplies, gross domestic products, trade account balances, and commodity prices have long been perceived as the determinants of the equilibrium exchange rate. Empirical studies such as that by Meese and Rogoff (1983) show that all current models perform poorly in explaining and forecasting short-run exchange rate movements.

Market microstructure models, applied widely across equity markets,[3] may provide a better understanding of exchange rate dynamics and better explain why intervention policies have not worked. These models have been slow to develop in the area of FX intervention.[4] This is surprising, since many of the arguments for intervention are firmly grounded in market microstructure theory. Microstructure models will make explicit that the behaviour of dealers and other market participants impacts on the effectiveness of intervention operations conducted by central banks. Private information and inventory controls are just two examples in which dealer behaviour affects price determination in the FX market. The purpose of this paper is to clarify the role and the impact of FX dealers in how central bank intervention affects nominal exchange rates. The effectiveness of intervention will depend on the ability of the monetary authority to predict the market's reaction.

The relationship between the behaviour of dealers and FX intervention flows is investigated using a unique dataset collected by the Bank of Canada that disaggregates trades by dealer and by customer type. The response of dealers to the trades of different customer types is analyzed to determine whether a unique response exists to central bank trades. The dataset provides an additional dimension of interest in that it covers two sample periods in which the Bank engaged in

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1. See Shwartz (2000) for a recent review of the literature and a record of past intervention episodes.
2. In Canada, Beattie and Fillion (1999) and Murray, Zelmer, and McManus (1997) test for the effectiveness of foreign exchange intervention and find that expected intervention had no direct impact on volatility, while discretionary unexpected intervention did reduce exchange rate volatility. Furthermore, over a short period of time, repeated unexpected intervention in the market was effective.
3. See O'Hara (1995) and Madhavan (2000).
4. Recent papers include Dominguez (1999) and Evans and Lyons (2000).

very different FX operations: intervention that was intended to impact on the nominal exchange rate, and intervention operations in the FX market to replenish lost reserves.[5]

The paper also attempts to determine whether customer trades, including central bank intervention, contain private payoff- and non-payoff relevant information, and whether dealers utilize this information strategically. Non-payoff-relevant information, such as about a dealer's relative inventory, is considered in Cao and Lyons (1999). Speculation is based on a dealer's ability to forecast the inventories of other dealers in the market. This ability helps dealers to forecast prices because it helps them to forecast the marketwide compensation for inventory risk. Any strategic behaviour on the part of dealers in response to central bank trades will impact on the effectiveness of intervention.

This paper is organized as follows. Section 2 describes the institutional features of the FX market, while section 3 describes the dataset utilized in the paper, and its sources. Section 4 presents stylized facts that depict the structure of the FX market in Canada. Section 5 describes the motivation for the market microstructure view of exchange rate determination, and develops two models to test various hypotheses about the behaviour of dealers and the information content of trade flows. Section 6 presents the empirical results from those tests. Section 7 offers some conclusions and describes some implications for policy.

2. Institutional Considerations and FX Intervention

The spot market in the overall Canadian FX market can be described as a decentralized multiple-dealership market, since it does not have a physical location where the dealers meet. Instead, it is a network of financial institutions or investors linked together by a high-speed communications system. Two important characteristics distinguish FX trading from trading in other markets: trades between dealers account for most of the trading volume and trade transparency is low. Since there are no disclosure requirements, the amount of information reflected in prices is reduced, allowing private information to be exploited for a longer time.

The players in the FX market include dealers, customers, and brokers. Dealers provide two-way prices to both customers and other dealers. In Canada, the top eight banks handle nearly all world-wide order flow (87 per cent) in the Can$/US$ spot market. Dealers receive private information through their customer's orders. Each dealer will know their own customer orders through the course of the day, and will try to deduce the positions of other dealers in the market. The customers are the financial and non-financial corporations that are the end-users of foreign

5. Note that the literature commonly calls the former type of intervention central bank intervention.

currencies for settling imports or exports, investing overseas, hedging business transactions, or speculating. Brokers[6] are the intermediaries who gather, buy, and sell information, and try to match the best orders among dealers. Brokers in the FX market are involved only in interdealer transactions, where they communicate dealer prices to other dealers without revealing the dealers' identities, as would be necessary in an interdealer trade. Brokers are pure matchmakers; they do not take positions on their own.

In addition to their own customers, dealers also learn about order flow from brokered interdealer trades. When a transaction exhausts the quantity available at the advertised bid/ask, the broker announces this fact. This indicates that a transaction was initiated. Though the exact size is not known, dealers have a sense of the typical size. Most importantly, this is the only public signal of market order flow in the FX market.

In Canada, recent intervention policy has sought to reduce the short-term volatility of the Can$/US$ exchange rate. Uncertainty among market participants about the future stance of monetary policy and extrapolative expectations of chartists are two possible causes of excessive volatility (Djoudad et al. 2001).

Appendix A.1 explains the mechanisms through which intervention can affect the exchange rate, and the historical record of intervention in Canada between 1995 and 1999; it also reviews research on the effectiveness of intervention. In general, empirical findings suggest that intervention has a small minimizing influence on exchange rate volatility when it is consistent with the underlying fundamentals of the economy.

3. Data

An important and powerful characteristic of the dataset employed in this paper is the level of disaggregated FX trade flows. The availability of the dataset provides a unique opportunity to test a number of recent hypotheses about the behaviour of dealers in FX markets. The source of the data is the Bank of Canada.[7] The dataset covers nearly four years of daily data (from January 1996 through September 1999), or 941 observations for the eight largest Canadian FX market participants. Trading flows (in Canadian dollars) are categorized by the institution type of each dealer's trading partners. Business transactions for Canadian FX dealers are broken down as follows: trade with the central bank (Bank of Canada) (CB); commercial client business (CC),

6. There are two main electronic interdealer broker systems: EBS and Reuters Dealing 2000-2.
7. The primary source of the dataset is the Bank's internal daily foreign exchange volume report. The report is coordinated by the Bank, and organized through the Canadian Foreign Exchange Committee (CFEC).

which includes all transactions with resident and non-resident non-financial customers; Canadian-domiciled investment flow business (CD), which are transactions with non-dealer financial institutions located in Canada, regardless of whether the institution is Canadian-owned; foreign-domiciled investment business (FD), which includes all transactions with financial institutions, including FX dealers, located outside Canada; and interbank (IB) business, which includes transactions with the domestic offices of other Canadian chartered banks, plus transactions with other financial institutions, such as credit unions, investment dealers, and trust companies, that are dealt with on a reciprocal basis in the interbank market.

Trade flows, or more specifically, net purchases of outright spot trades, are defined in this manner in an attempt to distinguish between trade-related and capital-related flows. The “type” of institution is used as a proxy for the type of transaction. In particular, commercial client business is defined so that there is particular emphasis on FX transactions related to commercial, or trade-related, activity. Canadian-domiciled investment flow business and foreign-domiciled investment business emphasize the investment, or capital, flow nature of those transactions.

In addition to trade flows, the analysis in this paper utilizes FX rate returns for the Can$/US$ exchange rate. These are continuously compounded returns, defined as the log difference of the exchange rate determined at the close of each business day. The measure of exchange rate volatility used in this paper is the implied volatility contained in FX money call options. This measure is a proxy for the expected volatility of the Can$/US$ exchange rate. Murray, Zelmer, and McManus (1997) state that “the advantage of this option-based approach over GARCH models is that it uses current market-determined prices that reflect the market’s true volatility forecast, rather than a time-series model that is based on an assumed relationship between future volatility and past exchange rate movements.” Data on interest rates (90-day treasury bill), oil prices, natural gas prices, and non-energy commodity prices are end-of-day prices obtained from the Bank of Canada (unless otherwise noted). The non-energy commodity price index constructed in this paper is a variant of the Bank’s commodity price index. This index includes only variables available at a daily frequency. It is the weighted average of the prices of barley, canola, corn, wheat, cattle, hogs, cod, lobster, aluminium, copper, gold, nickel, zinc, silver, and lumber. Weights[8] are in proportion to the commodities share of exports and imports. Natural gas prices are futures prices from contracts listed on the New York Board of Trade.[9]

8. See Amano and van Norden (1998).

9. Natural gas futures prices were obtained from Grain Market Research (http://www.grainmarketresearch.com/).

4. Stylized Facts

This section depicts the spot FX market in Canada through a number of descriptive statistics. The structure of the market portrayed in these statistics is an important ingredient when modelling the FX market. This is the market microstructure hypothesis. Tables 1 through 5 present various descriptive statistics for the Can$/US$ exchange rate and each type of trade flow in the Canadian FX market. The data are split into two samples. The subsamples used in the empirical tests throughout the paper were chosen on the basis of announced intervention regimes and data availability. The first sample includes the period 2 January 1996 to 30 September 1998. During that period, the Bank had set out intervention objectives and procedures that, although not publicly announced, were well known by the market. During the subsequent period, from 1 October 1998 to 30 September 1999, the Bank did not intervene in the FX market in an attempt to have an impact on exchange rates, but rather in an attempt to replenish its FX reserves.

During the first sample, the Bank intervened 80 out of 692 days (12 per cent of all business days). This compares with the second sample, in which the Bank replenished reserves 79 out of 250 days (32 per cent of all business days). In the earlier sample, 30 of the 80 days were occasions where the Bank used discretionary intervention. The Bank sold U.S dollars on 69 days and bought Canadian dollars on 11 days.

Table 1 reports descriptive data about the aggregate FX market and the eight dealers studied. The dealers are ranked from 1 to 8 by average total daily trading volumes (purchases plus sales) in the spot market over the 942 daily observations that spanned the whole dataset, with dealer 1 being the most active and dealer 8 the least active in the Canadian FX market.

Daily trading volumes and trading imbalances are presented in aggregate and broken down by type of business transaction (CB, CC, CD, FD, IB) and dealer. The mean, median, and standard deviations are presented for each variable. Medians are listed in addition to means and standard deviations because they are informative in skewed distributions. Trading volumes in the Canadian FX market have stayed nearly constant over the two sample periods. Approximately, Can$7.75 billion was transacted (purchases plus sales) daily among the eight dealers considered in this study. Interestingly, while domestic interbank trading has declined considerably (17 per cent decrease), Canadian dealers have increased their trading with foreign domiciled banks (including FX dealers located abroad) by around 10 per cent. Approximately 48 per cent of all trade (in the latter period) was with foreign domiciled financial institutions (up from 43 per cent in the intervention period). In contrast, approximately 25 per cent (down from 32 per cent in the intervention period) was trade among Canadian FX dealers. Business with commercial client and Canadian non-dealer financial institutions was steady over the two subperiods. Overall, these numbers indicate a growing influence of foreign domiciled financial institutions in the Canadian-dollar market.

While net daily trade flow totals for the different types of transactions declined over the two periods, the numbers are not significantly different from zero. This empirical regularity supports the frequent observation in the literature that dealers actively manage their inventories. They desire a nil inventory position at the end of the business day. Tables 2 and 3 show the correlations between the key variables in each period.

Test statistics for normally distributed variables (Tables 4 and 5) indicate evidence of skewness and kurtosis across all variables. Percentage changes in the exchange rate data consistently exhibit a high degree of kurtosis over all subsamples. The Box-Pierce Q-statistic tests for high-order serial correlation generally indicate that both the change and squared percentage changes in the exchange rate series exhibit significant autocorrelation. The latter is indicative of strong conditional heteroscedasticity. The first four sample autocorrelation and partial autocorrelation coefficients for the exchange rate series indicate homogeneous non-stationarity. The first lag of the sample partial autocorrelation is approximately one, and subsequent lags are close to zero. The statistics confirm that daily exchange rates are strongly heteroscedastic martingale processes. These findings are consistent with the previous literature. Standard Dickey-Fuller unit roots tests are performed on all variables and presented in Tables 6 and 8. Prices and the implied volatility variable were found to be non-stationary. In contrast, the hypothesis of a unit root in daily order flows is rejected in both periods at the 99 per cent significance level.

5. Microstructure Analysis

The importance of FX trades is new in the exchange rate literature. In the first part of this section, estimates of a typical exchange rate model are presented to motivate the market microstructure hypothesis. Later in this section, more substantive models will be considered to reveal the microstructure elements underlying the FX market and the behavour of exchange rates. The results in section 6 will illustrate that an approach in which the behaviour of dealers is modelled explicitly can uncover the reasons for the ineffectiveness of intervention operations by central banks.

The failure of traditional macroeconomic models to explain exchange rate movements suggests that a new approach is required. A new direction for research is proposed by Lyons (1997), who argues that exchange rate models should focus on information and institutions, where information incorporates both public and private information, and the term institutions refers to how the market is organized and how market participants acquire and aggregate non-public information. Unlike macroeconomic FX models, this microstructure approach acknowledges the existence of private information, and focuses on how this information is mapped into expectations of exchange rate movements.

Private information in the FX market may result from FX transaction orders. An order received by a dealer from a central bank at the onset of an episode of intervention is one example of potentially lucrative private trade-flow information. If the central bank is conducting secret intervention, the dealer would be privy to payoff-relevant information about the Bank's intentions with respect to exchange rates. Even if intervention is immediately transparent to the whole market, the trade order from the central bank may provide the dealer with an opportunity to speculate in the interdealer market. The market microstructure view of price determination predicts a continuous price path as the market gradually learns about changes in the overall market view of demand and supply from traders or order flow.

Trade and order flows are differentiated in this paper. Individual trade flows are defined as orders in the FX market between a certain type of customer and FX dealers. In contrast, order flow is defined as trade between all types of customers and dealers. Order flow can be thought of as a measure of net demand or imbalance across the whole FX market.

One measure of order flow employed in the literature (Evans and Lyons 2002, Hasbrouck 1991a,b) is the difference between buyer- and seller-initiated orders within the interdealer market. A sense of order flow is obtained by dealers through their own interdealer orders, but also from brokers. While trade flows are defined in this paper as the difference between purchases and sales among dealers and their various clients,[10]

$$\{CB_{it}, CC_{it}, CD_{it}, FD_{it}, IB_{it}\}\,, \tag{1}$$

order flow is the sum of net purchases across all dealers and all their clients throughout the day[11]:

$$V_t = \sum_i (CB_{it} + CC_{it} + CD_{it} + FD_{it} + IB_{it})\,. \tag{2}$$

10. Dealer trading is disaggregated by trade with the central bank (CB); commercial client business (CC); Canadian-domiciled investment flow business (CD); foreign-domiciled investment business (FD); and interbank or interdealer transactions (IB).

11. If the trade flow dataset were complete, net interdealer (IB) purchases across dealers would total zero.

Where $\{CB_{it}, CC_{it}, CD_{it}, FD_{it}, IB_{it}\}$ are dealer i's net purchases in period t. Specifically, the measure of order flow used in the analysis below assumes that the public is always initiating the trade as dealers are considered to be on the passive side of customer order flow.[12]

Why should order or trade flows matter when determining or predicting movements in the exchange rate? Later in this section, market microstructure models will be presented to demonstrate how trade flows, order flows, and exchange rates can be determined jointly in equilibrium. In this section, we draw only on the causal link from trade flows to exchange rates.

Lyons (1999) provides striking empirical results that show that marketwide order flow in the spot FX market (DM/US$ and Yen/US$), when cumulated over time, exhibit large and persistent departures from zero, and that order flow covaries positively with the exchange rate over horizons of days and weeks. Recall that macro fundamental models provide no role for trading, since macroeconomic information is publicly available and can therefore be impounded in exchange rates without trading. Lyons provides further statistical evidence in the spirit of traditional tests of structural models of exchange rate. A similar exercise is performed in this paper, but we disaggregate order flow into its individual net trade flow components. In a regression equation, trade flows (x_t) are included as regressors, in addition to traditional variables employed by the Bank, such as the 90-day treasury-bill interest rate differential between Canadian and U.S. oil prices, natural gas prices, and non-energy commodity prices, and a dummy variable for days in which intervention occurred. All variables except interest rates, the dummy variable, and trade flows are in log-levels:

$$\Delta \log S_t = a_0 + a_1(i_t - i_t') + a_2 \Delta oil_t + a_3 \Delta gas_t + a_4 \Delta non\text{-}eng_t + a_5 d_t + a_6 x_t + u_t . \qquad (3)$$

Regressions of this sort have long been the subject of study in the macro exchange rate literature (see Frankel and Rose 1995). If the macro approach is correct, estimates of a_6 should be insignificant. Lyons (1999) finds that they are in fact quite significant, which suggests that there is something to the microstructure approach to exchange rates. Here, the various customer dealer net trade flows are found to be highly significant in explaining movements in exchange rates.

Fitting a model, in-sample, is one thing, but forecasting out-of-sample is quite another, as many researchers have found. The evaluation criterion used in this paper was also used by Meese and Rogoff (1983) to evaluate a model's forecasting performance. The root-mean-squared forecast error (RMSE) of a model is

12. I thank Richard Lyons for this suggestion.

$$\left[\frac{1}{T}\sum_{t=k+1}^{T}(\Delta\hat{\log}S_t - \Delta\log S_t)^2\right]^{\frac{1}{2}}. \tag{4}$$

The out-of-sample forecasts generated by the model are later compared to that of a random walk. The model is initially estimated over part of the sample (the first *k* periods). Forecasts are then generated over the different time horizons of interest. A new observation is added to the sample (period *k+1*), the model is re-estimated, and again forecasts are generated. The process continues until it becomes impossible to forecast over all time horizons considered. A useful summary measure of the forecast performance of the model in the context of the RMSE is the Theil-U statistic, which is just the ratio of the model's RMSE to the random walk's RMSE. A value less than one implies that the model performs better than a random walk, whereas a value greater than one implies the reverse. The forecasts are conditional on ex-post information on future fundamentals and order flows.

Tables 7 and 9 present the least-squares estimates of equation (3) over the two sample periods. The first two regressions in each table include only traditional macroeconomic variables (and no trade flow variables) available at a daily frequency: interest rate differentials, crude oil prices, natural gas prices, non-energy commodity prices, and a dummy variable (included only in the second regression) for days in which the central bank conducted FX operations.

The coefficient estimates on all fundamental macroeconomic variables are negative, indicating that an increase in the Canadian-U.S. 90-day interest rate spread, oil prices, natural gas prices, or non-energy commodity prices will result in an appreciation of the Canadian dollar (over both sample periods). The dummy variable (equal to +1 on days in which dealers are purchasing Canadian dollars from the Bank, and -1 on days in which dealers are selling Canadian dollars to the Bank in return for U.S. dollars) was the only significant variable at the 95 per cent level, and had a negative coefficient in both regressions. On days in which the Bank was buying Canadian dollars the Canadian dollar depreciated, while on days in which the Bank was selling Canadian dollars the Canadian dollar appreciated.

The sign and significance of the macroeconomic variables are found to change little with the inclusion of trade flow variables (x_t) into the regression equation. In terms of the various trade flow variables, central bank trade flows (net purchases of Canadian dollars by dealers or, equivalently, net sales of Canadian dollars by the Bank) result in an appreciation of the Canadian dollar in the intervention and replenishment periods. The coefficients on central bank trade flows are highly significant, though the sign of the coefficient seems to be counterintuitive. Usually, intervention by the Bank is thought to have the opposite sign: purchases of Canadian dollars by the Bank should result in a decrease in the exchange rate or, in other words, lead to an appreciation of the Canadian dollar. Later, we demonstrate how this result can make sense in a microstructure framework. Finally, notice that in the last regression over the replenishment period the central bank dummy is not significant. In fact, replenishment operations by the Bank were conducted in very small amounts, to avoid influencing the exchange rate.

Commercial client trades have the same qualitative effect on the exchange rate as central bank flows, and the coefficient on the variable is statistically significant. In contrast, the coefficient on Canadian domiciled financial institution trade flows was not found to be significant in either sample period. The foreign domiciled financial institution trade flow coefficient has a positive sign (and is statistically significant), indicating that dealer purchases of Canadian dollars with this type of counterparty result in a depreciation of the Canadian dollar. Notice that net interbank purchases, which should roughly be zero on aggregate, are, not surprisingly, insignificant.

Adding the trade flow variables into the regression, together with macroeconomic variables, results in a dramatic increase in the explanatory power of the regression. In the intervention period, the R^2 of the equation jumps from less than 1 per cent (or 21.8 per cent with the inclusion of the dummy variable) to 35.2 per cent (or 38.4 per cent with a dummy variable), while in the replenishment period the numbers are 2.6 per cent and 39.5 per cent, respectively. It is not surprising that the traditional variables perform poorly. This is well documented in the literature. In contrast, the effect of the order flow variables on the explanatory power of the regression equation is remarkable.

While the in-sample fit of the exchange rate equation is important, the only true test of a model of the exchange rate is its performance out-of-sample. RMSEs and Theil-U statistics are calculated for both models across the two samples. The macroeconomic model performs about as well as the random-walk model. After order flow variables are added into the regression, the forecasting performance of the model changes dramatically, and is a significant improvement over the random-walk model. The forecasting exercise is performed by dividing each period (intervention and replenishment) into two equal subperiods. Equation (3) is estimated over the earlier subperiod, and forecasts over the various horizons are calculated for the different models. The process is repeated after extending the estimation period by an additional day. Again, equation (3) is estimated and forecasts are determined. The process is continued until forecasts over the different horizons can no longer be calculated. RMSEs can then be calculated.

The trade flow model's performance is superior at lower forecast horizons, but is still significantly better than the random-walk or the no-trade model at 40-period-ahead (8 weeks or 2 months) and

60-period-ahead (12 weeks or 3 months) horizons in both the intervention and replenishment periods. The overall results suggest not only that customer trades explain a significant proportion of the variability in exchange rates, but also that, judging from the forecasting performance of the model over long forecast horizons, customer trades must contain information about the fundamental value of the exchange rate currently not incorporated into the value of the exchange rate.

In sections 5.1 and 5.2, we provide two models that illustrate why central bank trades and other customer trade flows explain movements in exchange rates. In the first model, several features of the FX market are modelled explicitly: in particular, the reaction of dealers to trade orders from customers, and the process by which trade flows summarize information in the market across dealers. The second model is more general. Since no one model can capture every microstructure element of this complicated market, a framework that is robust to microstructure assumptions is developed to characterize the dynamics of trades, order flows, and exchange rates. Together, results from the two models help one to deduce the types of information that are available to dealers from customer trades, and the types of strategies that dealers subsequently engage in that will impact on exchange rate dynamics.

5.1 Simultaneous interdealer trading model

Consider a variant of the simultaneous trade model of the FX "hot potato" in Lyons (1997).[13] Although customer trades drive interdealer trading, it is the subsequent multiple periods of interdealer trading that provide real insight into the dynamics of the FX market. In the model, dealers behave strategically after receiving customer-dealer trades in the initial round of the model. A key feature of the model is that trading among dealers within a period occurs simultaneously. Simultaneous trading prevents dealers from conditioning their trades on the realization of the trades of others. Constraining conditioning information in this way also allows dealers to trade on information before it is reflected in price.

The payoff to holding FX, F, is realized after the second round of interdealer trading. The seven events of the model occur in the following sequence (see Figure 1):

Period one:

1. Dealers quote.
2. Customers trade with dealers.

13. Appendix A.2 contains a complete description of the model.

3. Dealers trade with dealers.
4. Interdealer order flow is observed.

Period two:

5. Dealers quote.
6. Dealers trade with dealers.
7. Payoff F is realized.

Customer market orders may not be independent of the payoff to the risky asset, F. Unlike in the Lyons (1999) model, it is assumed here that there are a number of customer "types." For example, commercial clients, non-dealer financial institutions, and central banks are all customers of dealers in the FX market. The net type-*k* customer order (e.g., central bank, commercial client) received by dealer *i* is

$$c_{ik} = F + \varepsilon_{ik} \qquad \varepsilon_{ik} \sim N(0, \sigma_{ik}) \qquad \forall k = 1 \ldots K. \tag{5}$$

c_{ik} is positive for net customer sales and negative for net purchases. Customer trades provide a noisy signal about the unobserved payoff to the risky asset, and are considered to be private information by each dealer. Quotes are required by all dealers markets. Refusing to quote violates an implicit contract of reciprocal immediacy and can be punished by reciprocating with refusals in the future.

The model's structure is designed around interdealer trading. Let T_{it} denote the net outgoing interdealer order placed by dealer i in period t, and let T_{it}' denote the net incoming interdealer order received by dealer i in period t, placed by other dealers. T_{it}' is positive for purchases by other dealers from dealer i. Since trading is simultaneous, T_{it} is not conditioned on T_{it}'. T_{it}' is an unavoidable disturbance to dealer i's position in period t that must be carried into the following period.

Notice that when dealers are determining their outgoing trade, they must consider both their desired amount, determined by private information, and their incoming c_{ik}'s and expectations of T_{i1}'. Trades with customers must be offset in interdealer trading to establish a desired position. Dealers must also do their best to offset the incoming dealer order, T_{i1}' (which they cannot know ex ante, owing to simultaneous trading).

An additional element of transparency in the model is provided at the end of each round of interdealer trading: interdealer order flow, V_1, is observed:

$$V_1 = \sum_{i=1}^{n} T_{i1}. \tag{6}$$

The sum over all interdealer trades, T_{i1}, is net interdealer demand—the difference in buy and sell orders. In FX markets, V_1 is the information on interdealer order flow provided by interdealer brokers.

Each dealer determines quotes and speculative demand by maximizing a negative exponential utility function defined over terminal wealth. The equilibrium concept used in this paper is that of a perfect Bayesian equilibrium (PBE). Equilibrium quotes and trades are

$$S_1 = \bar{F} \tag{7}$$

$$S_2 = \bar{F} + \lambda V_1 \qquad \lambda > 0. \tag{8}$$

Consider the following intuition for why $\lambda > 0$: each agent knows one component of V_1, specifically their own outgoing interdealer trade, which is a function of their customer orders. A negative observed V_1 means that, on average, T_{j1} is negative—dealers are selling in interdealer trading. This implies that, prior to interdealer trading, customers sold on average. Dealers are long on average in period 2. To clear the market, the expected return on holding FX must be positive to induce dealers to hold this long position $S_2 < \bar{F}$. The result is that the negative value of V_1 drives a reduction in price.

Since each dealer needs to account for his own impact on V_1, outgoing interdealer trades following customer dealers trades are

$$T_{i1} = \sum_k \beta_{1k} c_{ik} \qquad \beta_{1k} < -1 \qquad \forall k. \tag{9}$$

Suppose that a trader receives a customer order, c_i. If the trader sought only to hedge their risk, they would cover their position and choose $T_{i1} = -c_i$. But suppose that $V_1 = \sum_i T_{i1} < 0$. In this case, on average, all traders want to sell. To compensate for additional risk of holding on to the asset, prices must fall $S_2 < \bar{F} = S_1$. Knowing this, the agent strategically alters their outgoing order to capitalize on the higher return by choosing $T_{i1} > -c_i$.

In section 6, the behaviour of dealers is tested in light of the simultaneous interdealer trading model. Hypotheses are considered regarding the speculative and risk-sharing motives of dealers, the longevity of this behaviour subsequent to a customer trade, and whether the type of trade is important.

5.2 Vector autoregressions

It is impractical to model all features of the FX market jointly. This section strives to determine the impact of trades on exchange rates and exchange rate volatility in a framework that is robust to deviations from the assumptions of a formal model like that described in section 5.1. In the process, the framework establishes a rich characterization of the dynamics by which trades and exchange rates interact.

A vector autoregression (VAR) is constructed in this section to determine both the source of exchange rate variations and whether those variations are permanent or transitory. From an economic perspective, market prices can be interpreted as being informationally efficient prices perturbed by frictions of the trading process. New, fundamental information leads to a permanent revision to the expectation of the exchange rate, while microstructure effects are short-lived and transient. The response of exchange rates to a buy order will depend on the chances that the trade was initiated by positive information known by the buyer but unknown to the public. The proportion of the permanent price movement that can be attributed to trades is therefore related to the degree of payoff-relevant information asymmetry in the market. From a statistical viewpoint, it is measured by the explanatory power of trade-related variables in accounting for exchange rate variations. The transitory effects of a trade are perturbations induced by the trade that drive the current rate away from the corresponding informationally accurate permanent component price. Inventory control considerations induce transitory effects, as do order fragmentations or even private information about a dealer's inventory (D'Souza 2002a).

The VAR methodology also allows proper examination of the relationship between trade flows. Of particular interest are the flows generated among dealers (both domestic and foreign) subsequent to central bank trades and other customer trades. If tests indicate that interdealer flows are necessary to make the VAR complete, or that those flows are not exogenous, then this is evidence of the market microstructure view.

Numerous studies have already examined the dynamics of trades and stock prices (see Hasbrouck 1988, 1991a, b, 1993; Glosten and Harris 1998; Hasbrouck and Sofianos 1993; and Madhavan and Smidt 1991, 1993). A common approach of these studies is to assess the impact of trades on stock price, where any persistent impact presumably stems from the asymmetric payoff-relevant information signalled by trades. By examining trade flows in the Canadian FX market, this paper extends these studies in the direction of assessing the information content of the underlying determinants of trades.

The impact of the various trade flows on exchange rate returns cannot be judged from a linear regression of returns on current and lagged flows, because flows and returns are endogenous. For example, while an unexpected purchase of FX by a customer can lead to trade flows and exchange rate changes, the causality can also work in the other direction: an unexpected increase in the exchange rate can influence customer purchases. Thus, while a linear regression might give some insight into the expected return conditional on a given pattern in trade flows, it will not support an inference about the implied effect of a particular trade. In the present application, this limitation would preclude identification of the exchange rate effects attributable to the customer order. Thus, the model described in section 5.1 can explain only part of the overall dynamics of prices and trades (and the behaviour of dealers) in the FX market.

The VAR described in this section captures the dynamic relations among the variables and allows for lagged endogenous effects. The most useful statistics from this approach are: (i) impulse response functions, which are used to access the price impact of various trade flow types, and (ii) variance decompositions, which measure the relative importance of the variables in driving prices. In this paper, we judge the impact of different customer flows and the subsequent interdealer flows on exchange rate returns and volatility.

A VAR is a linear specification in which each variable in the model is regressed against lags of all variables. Letting z_t denote the column vector of model variables,

$$z_t = [c_t, FD_t, IB_t, V_t, returns_t], \tag{10}$$

the VAR specification can be written as:

$$z_t = A_1 z_{t-1} + A_2 z_{t-2} + \ldots + A_K z_{t-K} + \nu_t, \tag{11}$$

where the A_i's are coefficient matrices, K is the maximum lag length, and ν_t is a column vector of serially uncorrelated disturbances (the VAR innovations) with variance-covariance matrix Ω. The variable c_t is either net commercial client trade flows (CC), Canadian domiciled trade flows (CD), or central bank trade (CB), while the $returns_t$ variable is either exchange rate returns or per cent changes in implied volatility. While in reality there is probably a relationship between CC, CD, and CB trades, the various customers are entered in separate VARs to compare the effects of each type of customer order on interdealer trades, volumes, and returns. Foreign domiciled trade flows (FD) are entered in each VAR. These flows include trade with foreign FX dealers, who receive their own customer orders for Canadian dollars. Estimates of VAR coefficients and associated variance-covariance matrices can be obtained from least-squares. Appendix A.3 discusses VAR more thoroughly. Order flow or V_t is defined as

$$V_t = \sum_i (CB_{it} + CC_{it} + CD_{it} + FD_{it} + IB_{it}) . \qquad (12)$$

In the present work, hypothetical initial disturbances will be used to study the impact of particular market events. For example, the arrival of a customer trade to sell 1 million Canadian dollars at time t might be represented by letting $v_t = [1, 0, 0, 0, 0]'$. Setting the remaining components to zero would imply that the order has no contemporaneous impact on trades and returns. While this possibility exists, it is more likely that the order will engender a contemporaneous trade and a price revision. Ignoring the contemporaneous effect will lead to an understatement of the implied trade order impact.

The present analysis assumes that central bank trade disturbances, commercial client trade flows, and Canadian domiciled investment flows are each determined before foreign domiciled investment flows, marketwide order flow, and return disturbances. Assigning primacy to central bank trade, commercial client trade, or Canadian domiciled investment disturbances means that the effects of the other disturbances can only be considered to be incremental. Subsequent to these flows, foreign domiciled investment flow and domestic interbank innovations are determined. A variable representing market order flow is added to the VAR to reflect the information communicated to dealers through brokers (voice-based or electronic brokers). The variable considered is aggregate net trade. Innovations in net purchases of Canadian dollars in the FX market over the day are not permitted to affect the individual trade flows within that day, though they may affect exchange rate returns over the day. Lastly, any unexpected changes in the exchange rate over the day are not permitted to affect any of the other variables over the course of the day. This assumed ordering of the innovations is identical to the ordering in the z_t vector described above.

One hypothesis tested in this paper is whether the various customer trade flows have similar impacts on exchange rate returns. The hypothesis is tested by comparing the average price impact implied by the impulse response functions corresponding to different trade flow innovations. For ease of interpretation, the total size of each innovation is Can$1 million. In the discussion of structural innovations, the assumption was that central bank trade innovations (CB), commercial client trade flow innovations (CC), and Canadian domiciled investment flow (CD) are determined first, followed by foreign domiciled investment flow (FD), marketwide order flow, and return disturbances.

In addition to assessing the effect of particular innovations, it is also of interest to consider broader summary measures of the information contained in these trade flows; specifically, the impact of an innovation on the exchange rate net of any transient microstructure effects. The variance of this term is approximately equal to the return variance per unit time, with the return computed over an interval long enough that transient effects can be neglected. Alternatively, this is the variance of the random-walk component implicit in a security price, like the exchange rate, that behaves like a martingale:

$$S_t = S_{t-1} + w_t , \tag{13}$$

where w_t, the unforecastable increment, has the following properties: $Ew_t = 0$, $Ew_t^2 = \sigma_w^2$, and $Ew_t w_\tau = 0 \forall t \neq \tau$. This connection is developed more formally in Hasbrouck (1991b). Denoting this random-walk component as w_t, its variance can be computed as:

$$\sigma_w^2 = var(E[r_t + r_{t+1} + \ldots | \nu_t]) = \Psi_{\infty, r} \Omega \Psi_{\infty, r}'. \tag{14}$$

Although VARs are commonly used to characterize dynamic models, this approach also has limitations stemming from time aggregation, which leads to co-determined model disturbances and the consequent necessity of identification restrictions. The underlying economic model is based in continuous time. Although trades are discrete events, they can occur at any time. In principle, it would be necessary to specify a sampling interval fine enough to virtually preclude the simultaneous occurrence of events, and so minimize the problems of contemporaneous endogeneity. In practice, however, the time grid is dictated by the data availability.

To summarize, the VAR provides a tractable and comprehensive specification that is capable of capturing the dynamic relations among trade flows and exchange rate returns. Impulse response analysis is one useful way of characterizing a VAR in the present analysis, by constructing the implied price changes associated with the various types of trade flows. A second characterization of the exchange rate return specification in the VAR involves decomposing the sources of (long-run) return variation among the variables. Since returns are ultimately driven by changes in information, these analyses are useful in attributing information effects and the channels through which they operate.

6. Results

Two important findings are presented in this section. In section 6.1, the impact of central bank trades and other customer orders on dealer behaviour are evaluated using the simultaneous interdealer trading model described in section 5.1 as a guide. Results suggest that dealers use central bank intervention orders to trade strategically in the interdealer market with other dealers. Observed speculation is short-lived, suggesting that only non-payoff-relevant information is utilized by dealers, since the Lyons-type regressions described in section 5 point to the existence of payoff-relevant information in customer trades and the potential opportunity for dealers to make a profit. The VARs estimated in section 6.2 also point to payoff-relevant information in customer trades but not interdealer trades, though the latter are a crucial element that explain dynamics within the FX market.

6.1 Inventory-information model

Strategic speculation by dealer i based on the private information of its customer orders implies the following outgoing trades according to the theoretical model:

$$T_{i1} = \sum_k \beta_{1k} c_{ik} \qquad \beta_{1k} < -1 \qquad \forall k. \tag{15}$$

Although individual dealer data disaggregating incoming and outgoing interdealer trades $\{T_{it}, T_{it}'\}$ are not available in the Bank's dataset (see section 3), an assumption is made that allows a test of the model's predictions with the available net trade flows (T_{it}''), defined as trades between each dealer and all other dealers, $T_{it}'' \equiv T_{it} - T_{it}'$. Over the course of a day, it is assumed that dealers trade frequently enough among themselves that the only positions a dealer will be holding over the trading day are either speculative or positions owing to risk sharing. In particular, there are no expectational errors in incoming trades ($E_{i1}T_{i1}' = T_{i1}'$). Risk sharing arises because of the small finite number of dealers in the market that, as a group, must accommodate any total aggregate net customer order imbalance in the market. Exposure to FX rate changes are costly, so dealers share the risk. The allocation of risk across dealers will be determined by their aversion to risk and the price they receive to compensate them for the risk.

Consider the adjusted equation to (15):

$$T_{it}'' = \sum_k (\gamma_{k0} c_{ikt}) \ldots + \sum_k (\gamma_{kj} c_{ikt-j}) + \gamma_0 V_t \ldots + \gamma_j V_{t-j}, \tag{16}$$

where $c_k = \{CB, CC, CD, FD\}$. Ordinary least-squares (OLS) regressions of this equation allow joint tests of the effects of contemporaneous and lagged (j-lags) customer trades on dealer i's net trades. Individual dealer customer trades are disaggregated by type of trade in an effort to quantify their individual impact on dealer speculation efforts. The amount of risk sharing provided to the market by each individual dealer can be determined by the coefficients on total aggregate customer trades ($\gamma_0, \ldots, \gamma_j$).

The model predicts that $0 > \gamma_{k0} > -1$, whereas, if risk sharing exists, $1 > \gamma_0 > 0$. Specifically, if dealers did not engage in speculative behaviour, and instead perfectly hedged the risk exposure of their customer orders in the interdealer market, then $\gamma_{k0} = 0$. In the interdealer model illustrated in section 5.1, dealers do not just hedge but engage in profitable speculation in the interdealer market with the inventory information they hold from executing customer orders. Furthermore, dealers will also receive compensation in the form of expected exchange rate changes by sharing in the aggregate net demand position of the entire market at the end of the day, $\gamma_0 \neq 0$. Tables 10 and 12 present OLS estimates of equation (16) for each of the eight dealers in the sample in the spot FX markets. On the whole, the results support the hypothesis that there exist both contemporaneous dealer speculation based on private customer information and contemporaneous risk sharing (intervention period) among dealers. Most of the coefficients are statistically significant and have the predicted sign, though there is little evidence of lagged effects (four lags were employed). These results suggest that, although dealers engage in speculation, the length of time for which this activity is profitable is no more than one day.

In the intervention period, there is statistical evidence at the 95 per cent level that central bank trade flows were used by six of eight dealers for strategic reasons in their interdealer trading. In contrast, in the replenishment period, only one dealer's (the least active of the eight) coefficients on central bank trades was significant at the 95 per cent level. This change is also true across sample periods for commercial client trade, but not true with respect to Canadian and foreign domiciled investment flows. The change over sample periods in the central bank trade flow effects could be a result of the smaller-denominated orders in the latter period. In fact, replenishment is conducted in amounts that are intended to have little impact on the market.

The interdealer trade model explains anywhere from 7 to 21 per cent of the variations in interdealer trades across dealers in the intervention period. In the replenishment period, the numbers range from 2 to 15 per cent (ignoring dealer 8, who is found to be an outlier in most of our results). Lagged customer trades have little impact on today's interdealer trades over both samples, independent of the type of trade. In Tables 11 and 13, F-statistics are constructed to test whether the coefficients on contemporaneous central bank trade flows are equal to the coefficients on commercial client trade flows and Canadian domiciled financial institution trade flows. Across dealers and in both samples, in nearly all cases the null hypothesis that the coefficients were equal could not be rejected at the 95 per cent significance level. Again, dealer 8 (the least-active dealer) is the outlier. The implication of these results is that central bank trades are no different from other customer trades when dealers trade in interdealer markets.

Risk sharing is very evident in the intervention period but not in the replenishment period. In seven of eight individual dealer regressions, the coefficient on aggregate net customer orders was significant (the exception being dealer 8). In the replenishment period, only one of eight coefficients was significant at the 95 per cent level. Not surprisingly, the size of the coefficient on the order flow variable is negatively related to the total amount of trading that the dealer is engaged in (represented by the ordering of dealers in the table). The reduced risk-sharing finding, in the replenishment period among the dealers in our sample, conforms to a widely held belief in the FX market that domestic dealers in the last few years have lessened their reliance on formal domestic bilateral relationships. Instead, Canadian dealers have increased their use of electronic broker systems, possibly because those systems are more efficient at distributing risk in a marketplace that has seen greater and greater participation of foreign dealers (see section 5).

6.2 VAR estimation

When taking into account all possible relations between variables, it seems sensible to construct a model for a vector of time series. In cases where it is not known, a priori, which variable is affecting which, or when it is uncertain which variables are exogenous and which are endogenous, it seems useful to start with the construction of a general time-series model for a vector time series. In this subsection, we test whether private payoff-relevant information exists in trade flows, and whether dealers speculate with this information via interdealer trades. In section 6.1, we tested a model of interdealer trading in which dealers speculated in the interdealer market with private non-payoff-relevant information (such as their inventories). The implications of a interdealer trading model with private payoff-relevant information are identical to that of section 6.1. Therefore, we have not ascertained whether speculation is based on private payoff- or non-payoff-relevant information. We use the VAR methodology to shed light on this question.

VARs can be sensitive to lag length, or K in equation (11). The Akaike Information Criterion (AIC), defined as

$$AIC(K) = \ln(det\hat{\Omega}) + \frac{2n^2K}{T}, \tag{17}$$

where n is the number of variables in the system, T is the sample size, and $\hat{\Omega}$ is an estimate of the residual covariance matrix, is employed to determine the lag length of the VAR. The order is chosen to minimize the criterion. Usually one lag (and sometimes two lags) minimized the AIC criterion in each VAR estimated.

One of the key questions that can be addressed with VARs is how useful some variables are for forecasting other variables. A variable, x, is said to Granger-cause another variable, y, if the information in past and present x helps to improve the forecasts of the y variable. A block exogeneity test has as its null hypothesis that the lags on one set of variables do not enter the equations for the remaining variables. This is the multivariate generalization of Granger-Sims causality tests. The testing procedure used is the likelihood ratio test:

$$(T-c)(\log(|\Sigma_r|) - \log(|\Sigma_u|)), \tag{18}$$

where $|\Sigma_r|$ and $|\Sigma_u|$ are the restricted and unrestricted covariance matrices and T is the number of observations. This is asymptotically distributed as an χ^2 distribution with degrees of freedom equal to the number of restrictions. c is a correction to improve small sample properties. Sims (1980) suggests using a correction equal to the number of variables in each unrestricted equation in the system.

Block exogeneity tests are conducted on aggregate and dealer data, over both samples, using VARs that include central bank trade, foreign domiciled trade, interbank trade, marketwide trade, and either exchange rate returns or implied volatility returns. Three null hypotheses are tested: (i) dealer i interdealer trade flows are block exogenous, (ii) dealer i foreign domiciled trade flows are block exogenous, and (iii) marketwide order flows (V_t) are block exogenous. Results are presented in Table 14. In nearly all cases, the null hypotheses are rejected. Therefore, all VARs performed will include each of these variables. This result suggests that interdealer trade (domestic and foreign) and marketwide order flow are necessary in the price-discovery process.

The VAR specification described in the previous section (and slight variations in the specification) is estimated for all eight dealers in the sample. The coefficient estimates of the VAR are not reported, since little information is to be gained from them. Any one variable in the VAR can affect any other variable in the system either directly or indirectly through another equation. We instead focus on the impulse response functions and the variance decompositions.

Impulse response functions for exchange rate returns are computed in each sample subsequent to three different initial shocks. They are plotted in Figures 2 and 3. These shocks correspond to Can$1 million hypothetical spot market sell orders by a customer (either the central bank, a commercial client, or a Canadian domiciled (non-dealer) financial institution). The accumulated responses of exchange rate returns over 20 days are reported after each aggregate shock. As noted above, the long-term cumulative exchange rate return subsequent to a trade flow shock is interpreted as the information content of the order. The impulse response functions suggest that customer trade flows across both samples do indeed contain private payoff-relevant information about exchange rate returns. It will be necessary later to analyze whether the payoff-relevant information contained in these trades is utilized by dealers.

The impact of a central bank trade shock on exchange rate returns changes from one sample to the other. In the intervention period, a central bank trade of $1 million (dealers purchasing Canadian dollars and the central bank selling Canadian dollars) resulted in a permanent and statistically significant appreciation of the Canadian dollar of around 0.001 per cent, on average. The effect actually increases in the replenishment period by a factor of 6. In contrast, a $1 million commercial client or Canadian domiciled trade flow will result in, on average, less than a 0.0005 per cent appreciation of the exchange rate across both samples.

In addition to analyzing the relationship between trades, order flow, and exchange rate returns, a second VAR model is estimated. Again, trade and order flow variables are included, but their impact on (implied) volatility is determined instead. Impulse response functions in Figures 4 and 5 indicate that intervention operations by the Bank resulted in an immediate decrease in exchange rate volatility, which suggests that intervention operations had their desired effect in the first sample period. Specifically, these operations had a stabilizing effect on exchange rates. An additional implication of this result is that the signal sent by the monetary authorities through intervention operations was received uniformly across dealers. Replenishment operations had little impact on the volatility of the exchange rate.

Section 5.2 described a method for decomposing the long-run exchange rate return variance implied by the model into components attributable to the different model variables. Since the return variance is computed over an interval long enough to neglect transient effects, its components also measure the long-run or permanent explanatory power of each model variable. Therefore, if a variable explains only short-run transient variations in exchange rate changes, it will not perform well in the variance decompositions. These calculations are contingent on the identification restrictions governing the contemporaneous influences among the structural innovations. For each dealer in the sample, a relative variance decomposition is computed corresponding to equation (41) in Appendix A.3.

Customer trades (CB, CC, CD) do not enter into the VARs together. Each is included separately, along with interdealer and foreign domiciled investment trade. This assumption is made to allow a comparison of the relative impact of central bank trades with other customer trade flows. Clearly, each of these trade flows is integral in explaining the dynamics of the Canadian FX market, but the effect of each of these largely independent flows on interdealer flows, marketwide order flow, and exchange rate returns is essential.

In each VAR, five variables are included in the following order: customer net trade (CB, CC, or CD), foreign domiciled net trade, interbank net trade, marketwide order flow, and per cent changes in either exchange rates or implied volatility. Foreign domiciled trade is not included as a customer trade in these VARs, since those flows can include trades by foreign dealer banks that make a market in Canadian dollars. Canadian dealers can use foreign dealers to speculate with or to risk share.

The relative variance components, the R^2s in equation (41) in Appendix A.3, are reported in Tables 15 to 38. Tables 15 to 22 focus on one aspect of the VAR ordering. Specifically, given the high correlation between central bank trades and the central bank intervention dummy variable (67.18 per cent in the intervention period, and 73.50 per cent in the replenishment period), a pair of decompositions with those two variables placed next to each other is performed, changing only the positions of the two variables from one VAR to the next. Since the combined explanatory power of the two variables is independent of which variable comes first, how the variance is split between them can be examined.[14] In the intervention period, the dummy variable explains exchange rate returns better than the central bank trade variable when placed second in the VAR (Tables 15 and 19). This is evidence that the dummy variable is the causative factor, and the trade variable moves closely with it. Therefore, it is not the actual trade by the central bank that effects the exchange rate, but the signal received by the market once the central bank decides to intervene. In contrast, during the replenishment period (Tables 16 and 20), the central bank trade variable explains exchange rate returns better than the dummy variable when placed second in the VAR. The result is consistent, given the importance the Bank places on accurately informing the market that replenishment activities are not meant to have an impact on the exchange rate.

The large proportion of the relative variance of the exchange rate explained by central bank trades must arise from the signal implicit in those trades about the future course of Bank policy. Given the results, this would imply that replenishment operations by the Bank were also giving the market a signal about future policies.

From pages 43 to 48, the bottom two tables on each page look at the impact of trade flows on the percentage change in (implied) volatility rather than the exchange rate returns in the two sample

14. This technique is explained in Doan (1992).

periods. The stated objective of the Canadian authorities in the intervention sample period was to affect the volatility of the exchange rate. Central bank trades are found to impact on the volatility of the exchange rate only in the intervention sample period (consistent qualitatively with the impulse response functions in Figures 4 and 5).

Variance decomposition results across customer trade types are shown in Tables 23 to 38 by sample, and by whether the variance decompositions focus on variance in exchange rate returns or variance in the percentage change in volatility. A comparison of variance decomposition results between other customer orders and central bank orders can now be made. Central bank trade flows explain the largest proportion of the relative variance in exchange rate returns (in terms of customer orders), followed by commercial client trade flows. The differences are large across the types of customer trade flows, but not across the two samples.

The most important observation within these tables is the small incremental contribution of interdealer trade flows and marketwide order flow across all variance decompositions. This result suggests a small role for these components in the long-run price-discovery process. Specifically, it suggests that although private payoff-relevant information does exist in customer trades (as exhibited by the permanent effect of customer trade shocks in the impulse response functions), speculation among dealers in the FX markets (which was illustrated in section 6.1) is based more on transient non-payoff-relevant information, such as an individual dealer’s inventory level.

7. Conclusions and Implications for Policy

This paper has tested a number of microstructure theories concerned with the impact of central bank intervention on the behaviour of exchange rates. The vast majority of research in this area indicates that such policies have had little success. Further, the reasons for their failure are not clear. The issue is certainly related to the shortcomings of macroeconomic models of the determination of the exchange rate. This paper has demonstrated that a detailed analysis of how dealers in the FX market behave or react to central bank trades can shed light on why intervention policies have been ineffective in the past, and on how they may be adjusted in the future to attain their desired result.

Employing a dataset that disaggregates trades between individual dealers and their customers by type of customer, the paper tested how dealers responded to customer orders across two separate sample periods. In the earlier period, the Bank intervened to influence the volatility of the exchange rate, while in the latter period, replenishment operations were conducted. The disaggregation by type of customer trade is an important feature of the analysis. It determines whether central bank operations should be analyzed differently than another customer order in future research. Findings suggest that FX dealers behave in a similar strategic manner when they receive customer trades, independent of whether they originate from a central bank, a domestic firm, a foreign dealer or customer, or another domestic dealer in the FX market. In particular, this paper has demonstrated that dealers use their own customer trades as a source of non-payoff-relevant private information, which imparts a temporary profit-making opportunity to dealers speculating in the interdealer market. The strategy is not profitable for long. Results suggest that informed speculative trading will not last longer than a day.

Evidence suggests that the domestic dealers in the FX are also motivated in their trading strategies by the need to share inventory risk. While this is evident in the early part of the data, it is not as clear in the latter part of the sample, possibly because of the greater participation of foreign dealers in the market. This finding is consistent with the results of the variance decomposition analysis that suggests that foreign dealers have over time had a larger impact on exchange rate returns in the Canadian-dollar market.

This paper's VAR analysis suggests that private payoff-relevant information also exists in customer trades, including central bank trades. The same conclusion is drawn from the results of the forecasting performance of a prototypical exchange rate equation when trade flow variables are included as regressors. These models do extremely well in terms of their explanatory power and their forecasting performance, even at three-month forecast horizons, because the trade flow variables contain fundamental information about the value of the exchange rate.

Evidence that trade flows contain payoff-relevant information and that dealer speculation is only short-lived suggests that the payoff-relevant information in customer-dealer trades is not precise enough to compensate dealers for the risk that they must bear if speculation is based on this information. The implication for central bank intervention is that, aside from the signal that is immediately conveyed to the market as a result of intervention, any payoff-relevant information in central bank trade flows will not be reflected in prices by interdealer trades. This information is not considered by dealers to be a profitable risk-adjusted opportunity.

The implications of the overall results for central bank intervention are as follows: if a central bank wishes to use intervention to signal policy, interdealer trading behaviour effects will arise in the market. In particular, if the central bank wishes to reduce the volatility of the exchange rate, aside from credibly signalling a policy that reduces the diversity of opinions among FX participants, intervention flows on their own may have the opposite effect. The optimal strategy of each dealer is to amplify any customer trades in interdealer trading. If the central bank is more concerned about the supply of liquidity in the market, then, given the above-noted behaviour of dealers, the central bank will be aided by dealers in its pursuit. In either case, a central bank must be able to forecast overall net customer trades in the market if they are to be effective. This will be increasingly difficult given the greater participation of foreign dealers in the market and the greater use of electronic brokers by dealers to anonymously trade undesired positions.

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Table 1: Descriptive Statistics (Can$ millions)

Regime:	**Sample period 1: 2 Jan. 1996–30 Sep. 1998**			**Sample period 2: 1 Oct. 1998–30 Sep. 1999**		
Variables	**Mean**	**Median**	**Std. dev.**	**Mean**	**Median**	**Std. dev.**
Aggregate trading volumes						
Cen. bank1	27.00	0.00	107.85	0.00	0.00	0.00
Cen. bank2	0.00	0.00	0.00	18.94	0.00	37.98
Total	7722.51	7203.50	3173.54	7778.08	7327.00	2398.22
Interbank	2434.16	2251.30	1232.73	2018.98	1811.95	938.83
Foreign	3385.70	3179.60	1566.97	3719.79	3561.85	1296.52
Com. client	1537.04	1462.40	524.66	1639.18	1533.50	635.27
Can. dom.	338.61	296.00	190.45	381.19	346.40	169.34
Aggregate net trade						
Cen. bank1	-16.18	0.00	110.00	0.00	0.00	0.00
Cen. bank2	0.00	0.00	0.00	18.94	0.00	37.98
Order flow	130.09	79.20	429.92	37.41	13.40	569.43
Interbank	15.38	16.40	193.09	-1.99	-6.60	140.30
Foreign	122.66	100.90	471.79	49.87	30.40	419.69
Com. client	-16.36	-23.20	232.68	-44.95	-86.45	495.76
Can. dom.	24.58	14.70	113.60	15.54	9.05	119.69
Net trade, central bank intervention						
Dealer 1	-6.49	0.00	41.26	0.00	0.00	0.00
Dealer 2	-2.06	0.00	21.20	0.00	0.00	0.00
Dealer 3	-3.78	0.00	29.25	0.00	0.00	0.00
Dealer 4	-1.72	0.00	19.79	0.00	0.00	0.00
Dealer 5	-1.47	0.00	12.72	0.00	0.00	0.00
Dealer 6	-0.25	0.00	3.08	0.00	0.00	0.00
Dealer 7	-0.13	0.00	2.48	0.00	0.00	0.00
Dealer 8	-0.29	0.00	6.38	0.00	0.00	0.00

(continued)

Table 1: Descriptive Statistics (Can$ millions)

Regime:	**Sample period 1: 2 Jan. 1996–30 Sep. 1998**			**Sample period 2: 1 Oct. 1998–30 Sep. 1999**		
Variables	**Mean**	**Median**	**Std. dev.**	**Mean**	**Median**	**Std. dev.**
Net trade, central bank replenishment						
Dealer 1	0.00	0.00	0.00	3.39	0.00	11.45
Dealer 2	0.00	0.00	0.00	2.82	0.00	9.47
Dealer 3	0.00	0.00	0.00	2.38	0.00	8.94
Dealer 4	0.00	0.00	0.00	3.47	0.00	12.12
Dealer 5	0.00	0.00	0.00	2.88	0.00	9.54
Dealer 6	0.00	0.00	0.00	1.13	0.00	4.75
Dealer 7	0.00	0.00	0.00	1.42	0.00	5.62
Dealer 8	0.00	0.00	0.00	1.45	0.00	5.50
Net trade, total						
Dealer 1	19.58	21.10	170.67	-9.17	-0.75	188.14
Dealer 2	14.27	5.00	172.49	26.19	1.00	453.43
Dealer 3	35.49	22.00	204.41	-3.94	-4.00	154.76
Dealer 4	21.05	12.70	143.57	8.08	12.50	136.15
Dealer 5	14.58	8.00	142.32	-2.14	-3.00	147.37
Dealer 6	9.44	3.70	56.66	10.59	3.60	58.16
Dealer 7	14.39	8.10	62.95	23.37	15.20	61.80
Dealer 8	1.30	0.00	75.30	-15.57	0.00	75.50
Net trade, interbank						
Dealer 1	-9.29	-8.10	144.04	-11.89	-11.85	138.79
Dealer 2	-8.48	-8.00	134.46	-0.32	5.00	84.56
Dealer 3	15.10	10.00	117.75	12.99	3.19	114.69
Dealer 4	1.46	1.70	115.76	-3.04	-0.05	122.88
Dealer 5	12.40	0.00	102.75	-4.85	-1.00	86.73
Dealer 6	4.30	4.50	40.22	5.99	3.80	41.60
Dealer 7	-2.49	-3.00	44.39	0.57	-2.95	50.68
Dealer 8	2.38	0.00	61.67	-1.42	0.00	6.41

(continued)

Table 1: Descriptive Statistics (Can$ millions)

Regime:	Sample period 1: 2 Jan. 1996–30 Sep. 1998			Sample period 2: 1 Oct. 1998–30 Sep. 1999		
Variables	**Mean**	**Median**	**Std. dev.**	**Mean**	**Median**	**Std. dev.**
Net trade, foreign domiciled						
Dealer 1	23.99	23.40	148.91	12.56	12.55	160.04
Dealer 2	33.32	25.00	179.18	0.97	8.00	114.92
Dealer 3	31.78	20.00	203.45	7.44	8.50	129.23
Dealer 4	15.58	7.50	118.80	24.85	20.65	106.50
Dealer 5	10.89	2.00	104.13	6.34	0.00	84.28
Dealer 6	8.65	4.90	50.95	5.81	0.05	54.34
Dealer 7	0.62	0.40	45.14	9.79	2.05	43.84
Dealer 8	-2.17	0.00	80.45	-17.88	0.00	71.94
Net trade, commercial clients						
Dealer 1	0.40	-7.10	95.63	-19.49	-18.55	94.25
Dealer 2	-12.67	-14.00	87.70	18.76	-16.00	443.48
Dealer 3	-14.01	-13.00	116.01	-36.74	-39.00	95.09
Dealer 4	0.78	-1.30	68.33	-8.39	-3.60	49.44
Dealer 5	-5.99	-4.00	83.29	-7.49	-13.50	105.48
Dealer 6	-4.12	-3.90	31.30	-3.53	-5.20	26.13
Dealer 7	18.04	11.10	41.88	11.22	6.80	32.25
Dealer 8	1.21	0.00	23.45	0.70	0.00	20.07
Net trade, Canadian domiciled						
Dealer 1	10.98	5.40	56.22	6.27	2.55	53.66
Dealer 2	4.16	2.00	52.86	3.96	5.50	37.51
Dealer 3	6.40	2.00	47.68	10.00	2.00	57.21
Dealer 4	4.95	0.10	44.25	-8.81	-0.15	64.52
Dealer 5	-1.26	0.00	53.06	0.98	0.00	34.84
Dealer 6	0.85	0.00	20.19	1.20	0.30	10.52
Dealer 7	-1.66	0.00	12.08	0.37	0.00	4.08
Dealer 8	0.16	0.00	18.17	1.57	0.00	18.74

Table 2: Correlations

Sample period 1								
Exchange rate	1.00							
Exchange rate returns	-0.03	1.00						
Central bank net trade	-0.34	-0.04	1.00					
Order flow	0.04	0.01	-0.15	1.00				
Interbank net trade	0.02	0.01	-0.05	0.19	1.00			
Foreign domiciled net trade	0.06	-0.01	-0.39	0.75	-0.11	1.00		
Commercial client net trade	0.01	0.05	0.10	0.16	-0.14	-0.34	1.00	
Canadian domiciled net trade	0.16	0.02	-0.00	0.16	0.02	-0.13	0.05	1.00

Table 3: Correlations

Sample period 2								
Exchange rate	1.00							
Exchange rate returns	0.11	1.00						
Central bank net trade	-0.33	-0.01	1.00					
Order flow	0.16	-0.08	-0.14	1.00				
Interbank net trade	0.00	0.01	-0.02	0.18	1.00			
Foreign domiciled net trade	0.15	-0.02	-0.36	0.46	-0.11	1.00		
Commercial client net trade	0.08	-0.05	0.06	0.73	0.04	-0.19	1.00	
Canadian domiciled net trade	0.01	-0.10	0.01	-0.07	-0.09	-0.27	-0.06	1.00

Table 4: Time-Series Properties: Sample Period 1

z	S_t	$\Delta \ln S_t$	**CB net trade**	**Order flow**	**IB net trade**	**FD net trade**	**CC net trade**	**CD net trade**
Skewness	**1.33	0.08	**-4.08	**1.96	**0.46	**1.22	**-0.42	0.07
Kurtosis	**1.30	**3.51	**50.3	**16.9	**3.70	**8.61	**3.67	**8.87
$Q_{\Delta z}(15)$	**9191	**34	**247	**52.8	16.74	**48.3	21.84	**32.5
$Q_{(\Delta \ln z)^2}(15)$	**9167	**243	**169	3.46	20.98	2.42	**25.1	5.80
Autocorrelations	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.99	0.05	0.26	0.08	0.01	0.16	0.10	-0.01
	0.98	0.03	0.14	0.11	0.06	0.07	0.03	0.05
	0.97	0.04	0.26	0.03	0.01	0.07	0.04	-0.03
	0.96	-0.07	0.09	0.01	0.03	0.00	0.05	0.01
Partial auto-correlations	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.99	0.05	0.26	0.08	0.01	0.16	0.10	-0.01
	0.07	0.03	0.07	0.10	0.06	0.05	0.02	0.05
	-0.01	0.04	0.22	0.02	0.01	0.06	0.04	-0.03
	-0.03	-0.08	-0.03	0.00	0.03	-0.02	0.04	0.00

Notes: The skewness and kurtosis statistics are normalized so that a value of 0 corresponds to the normal distribution. $Q_{\Delta z}(15)$ pertains to the Box-Pierce Q-statistic test for high-order serial correlation in Δz; * denotes significance at the 95 per cent level; ** denotes significance at the 99 per cent level.

Table 5: Time-Series Properties: Sample Period 2

z	S_t	$\Delta \ln S_t$	**CB net trade**	**Order flow**	**IB net trade**	**FD net trade**	**CC net trade**	**CD net trade**
Skewness	0.12	*0.38	**2.28	**7.59	**-1.63	-0.03	**11.1	-0.18
Kurtosis	**-1.18	**1.43	**4.60	**94.2	**11.5	**2.72	**155	**3.84
$Q_{\Delta z}(10)$	**1918	12.03	**43.1	8.23	1.82	**70.1	5.27	5.84
$Q_{(\Delta \ln z)^2}(10)$	**1917	14.41	**24.4	0.13	3.52	14.8	0.07	14.91
Autocorrelations	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.97	-0.05	0.28	0.07	0.00	0.37	-0.07	0.00
	0.94	-0.04	0.09	0.06	0.03	0.24	0.03	-0.07
	0.91	0.03	0.00	0.12	-0.05	0.19	0.04	0.03
	0.89	0.20	0.09	0.01	-0.00	0.12	0.07	-0.01
Partial auto-correlations	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.97	-0.05	0.28	0.07	0.00	0.37	-0.07	0.00
	0.02	-0.04	0.01	0.05	0.03	0.11	0.02	-0.07
	-0.01	0.02	-0.03	0.11	-0.05	0.08	0.04	0.03
	0.00	0.00	0.22	-0.00	-0.00	0.01	0.07	-0.01

Notes: The skewness and kurtosis statistics are normalized so that a value of 0 corresponds to the normal distribution. $Q_{\Delta z}(15)$ pertains to the Box-Pierce Q-statistic test for high-order serial correlation in Δz; * denotes significance at the 95 per cent level; ** denotes significance at the 99 per cent level.

Table 6: ADF Unit Root t-tests, Sample Period 1

Variable	t-test	Lags(f)	Variable	t-test	Lags(f)
Exchange rate level	0.55	0	Exchange rate returns	**-25.17	0
Implied volatility	-0.19	2	Implied volatility (per cent change)	**-29.95	0
Interest rate differential	-1.20	6	Change in interest rate differential	**-16.52	5
Oil price	-1.74	0	Oil price returns	**-20.82	1
Natural gas prices	-1.67	0	Natural gas price returns	**-25.23	0
Non-energy commodity prices	0.01	0	Non-energy commodity price returns	**-20.56	1
CB	**-10.22	2	FD	**-22.26	0
CC	**-23.50	0	IB	**-25.61	0
CD	**-26.34	0	TRAD	**-15.93	0

Note: Critical values are from Hamilton (1994): *-3.43 (1 per cent), **-2.86 (5 per cent).

Table 7: In-Sample Fit and Out-of-Sample Forecasting Performance, Sample Period 1

Variable	No trade flows	No trade flows - CB dummy	Trade flow variables	Trade flow variables - CB dummy
Constant ($a_0 \times 10^{-4}$)	1.61 (0.12)	-1.63 (0.08)	-2.04 (0.02)	-0.02 (0.75)
Interest rate changes ($a_1 \times 10^{-1}$)	-0.41 (0.37)	-0.67 (0.11)	-0.69 (0.06)	-0.73 (0.04)
Oil price returns ($a_2 \times 10^{-2}$)	-0.48 (0.18)	-0.22 (0.52)	-0.04 (0.89)	0.10 (0.75)
Natural gas returns ($a_3 \times 10^{-2}$)	-0.45 (0.08)	-0.26 (0.25)	-0.43 (0.04)	-0.36 (0.08)
Non-energy returns ($a_4 \times 10^{-2}$)	-0.58 (0.54)	-0.07 (0.93)	-0.69 (0.40)	-0.46 (0.57)
Central bank trade dummy ($a_5 \times 10^{-2}$)		-0.39 (0.00)		-0.21 (0.00)
Central bank trade ($a_6 \times 10^{-6}$)			-6.46 (0.00)	-3.10 (0.23)
Commercial client trade ($a_7 \times 10^{-6}$)			-2.02 (0.00)	-1.98 (0.00)
Canadian domiciled trade ($a_8 \times 10^{-6}$)			-0.84 (0.29)	-1.10 (0.16)
Foreign domiciled trade ($a_9 \times 10^{-6}$)			1.89 (0.00)	1.68 (0.00)
Interbank trade ($a_{10} \times 10^{-6}$)			-0.78 (0.34)	-0.97 (0.22)
$\bar{R}^2$	0.004	0.218	0.352	0.384
Theil-U: 1-period ahead forecast	1.0007	0.855	0.6707	0.6769
Theil-U: 2-period ahead forecast	0.9995	0.857	0.6694	0.6759
Theil-U: 4-period ahead forecast	1.0024	0.858	0.6734	0.6811
Theil-U: 5-period ahead forecast	1.0028	0.872	0.6745	0.6886
Theil-U: 10-period ahead forecast	0.9999	0.863	0.6654	0.6786
Theil-U: 20-period ahead forecast	1.0003	0.884	0.6761	0.6959
Theil-U: 40-period ahead forecast	0.9906	0.858	0.7534	0.7313
Theil-U: 60-period ahead forecast	0.9968	0.837	0.7413	0.7223

Notes: Standard errors are corrected for heteroscedasticity. *p*-values are listed in parentheses below estimated coefficients. Theil-U statistic is the ratio of the model's RMSE relative to the RMSE of a random walk.

Table 8: ADF Unit Root t-tests, Sample Period 2

Variable	t-test	Lags(f)	Variable	t-test	Lags(f)
Exchange rate level	-1.54	0	Exchange rate returns	-16.42	0
Implied volatility	-2.30	0	Implied volatility (per cent change)	-17.50	0
Interest rate differential	-2.86	1	Change in interest rate differential	-11.34	5
Oil price	-0.82	0	Oil price returns	-15.69	0
Natural gas prices	-1.28	0	Natural gas price returns	-15.61	0
Non-energy commodity prices	-0.80	1	Non-energy commodity price returns	-13.16	0
CB	-10.22	0	FD	-10.58	0
CC	-16.94	0	IB	-16.09	0
CD	-15.98	0	TRAD	-15.93	0

Note: Critical values are from Hamilton (1994): -3.43 (1 per cent), -2.86 (5 per cent), -2.57 (10 per cent).

Table 9: In-Sample Fit and Out-of-Sample Forecasting Performance, Sample Period 2

Variable	**No trade flows**	**No trade flows - CB dummy**	**Trade flow variables**	**Trade flow variables - CB dummy**
Constant ($a_0 \times 10^{-4}$)	-0.82 (0.74)	8.29 (0.02)	4.27 (0.07)	2.98 (0.25)
Interest rate changes ($a_1 \times 10^{-1}$)	-0.02 (0.29)	-1.73 (0.21)	-1.22 (0.31)	-1.17 (0.33)
Oil price returns ($a_2 \times 10^{-2}$)	-2.00 (0.08)	-1.24 (0.24)	-0.84 (0.34)	-0.88 (0.32)
Natural gas returns ($a_3 \times 10^{-2}$)	-0.10 (0.24)	-0.77 (0.31)	-0.92 (0.13)	-0.97 (0.11)
Non-energy returns ($a_4 \times 10^{-2}$)	-4.54 (0.08)	-4.83 (0.04)	-0.01 (0.98)	0.35 (0.86)
Central bank trade dummy ($a_5 \times 10^{-2}$)		-0.29 (0.00)		0.08 (0.34)
Central bank trade ($a_6 \times 10^{-6}$)			-4.09 (0.00)	-4.80 (0.00)
Commercial client trade ($a_7 \times 10^{-6}$)			-1.12 (0.00)	-1.09 (0.00)
Canadian domiciled trade ($a_8 \times 10^{-6}$)			-0.10 (0.64)	-0.89 (0.67)
Foreign domiciled trade ($a_9 \times 10^{-6}$)			3.10 (0.00)	3.16 (0.00)
Interbank trade ($a_{10} \times 10^{-6}$)			-0.83 (0.66)	-0.96 (0.61)
$\bar{R}^2$	0.026	0.136	0.395	0.397
Theil-U: 1-period ahead forecast	1.0199	0.878	0.5481	0.589
Theil-U: 2-period ahead forecast	1.0152	0.872	0.5482	0.588
Theil-U: 4-period ahead forecast	1.0045	0.869	0.5760	0.613
Theil-U: 5-period ahead forecast	1.0055	0.873	0.5790	0.622
Theil-U: 10-period ahead forecast	1.0030	0.880	0.6114	0.650
Theil-U: 20-period ahead forecast	1.0280	0.881	0.5817	0.627
Theil-U: 40-period ahead forecast	1.0048	0.866	0.5884	0.648
Theil-U: 60-period ahead forecast	0.9607	0.842	0.5898	0.627

Notes: Standard errors are corrected for heteroscedasticity. *p*-values are listed in parentheses below estimated coefficients. Theil-U statistic is the ratio of the model's RMSE relative to the RMSE of a random walk.

Table 10: OLS Estimates of Reduced Form Equations of Lyon's Model, Sample Period 1

	Con.	CB	CB lags	CC	CC lags	CD	CD lags	FD	FD lags	Order flow	Order flow lags	$\bar{R}^2$
1	-17.65	-0.35	-0.04	-0.49	-0.04	-0.31	-0.05	-0.41	0.02	0.09	0.01	0.19
	(0.00)	(0.00)	(0.93)	(0.00)	(0.41)	(0.00)	(0.72)	(0.00)	(0.80)	(0.00)	(0.68)	
2	-9.55	-0.76	0.10	-0.45	0.07	-0.43	0.04	0.38	0.05	0.07	-0.03	0.21
	(0.08)	(0.01)	(0.91)	(0.00)	(0.23)	(0.00)	(0.91)	(0.00)	(0.23)	(0.00)	(0.23	
3	14.42	-0.35	0.00	-0.48	0.09	-0.20	0.04	-0.20	0.05	0.07	-0.03	0.19
	(0.00)	(0.00)	(0.85)	(0.00)	(0.12)	(0.00)	(0.40)	(0.00)	(0.06)	(0.00)	(0.08)	
4	4.44	-0.52	0.17	-0.27	0.17	-0.54	-0.04	-0.27	0.00	0.04	0.01	0.10
	(0.38)	(0.03)	(0.82)	(0.00)	(0.09)	(0.00)	(0.92)	(0.00)	(0.69)	(0.00)	(0.81)	
5	8.91	-0.62	-0.04	-0.35	0.06	-0.24	0.12	-0.13	0.07	0.02	-0.01	0.10
	(0.04)	(0.04)	(0.43)	(0.00)	(0.13)	(0.00)	(0.45)	(0.00)	(0.18)	(0.00)	(0.48)	
6	-2.90	0.07	0.99	-0.42	0.01	-0.07	0.00	-0.22	0.02	0.01	0.00	0.14
	(0.09)	(0.87)	(0.31)	(0.00)	(0.16)	(0.27)	(0.99)	(0.00)	(0.57)	(0.00)	(0.85)	
7	-1.86	0.17	0.98	-0.12	0.02	-0.22	0.12	-0.25	-0.07	0.01	0.00	0.07
	(0.42)	(0.78)	(0.12)	(0.01)	(0.86)	(0.10)	(0.75)	(0.00)	(0.19)	(0.03)	(0.40)	
8	0.60	-1.70	-0.29	-0.12	-0.01	0.01	0.02	-0.12	0.07	0.01	-0.00	0.08
	(0.57)	(0.00)	(0.90)	(0.01)	(0.97)	(0.64)	(0.79)	(0.00)	(0.83)	(0.77)	(0.62)	

Note: *p*-values for *t*-tests (contemporaneous coefficients are zero) and F-tests (lag coefficients are zero) are listed in parentheses below the estimated coefficients.

Table 11: F-Statistics; Reduced Form Equations of Lyon's Model, Sample Period 1

	CB=CC	CB=CD		CB=CC	CB=CD		CB=CC	CB=CD		CB=CC	CB=CD
1	1.05	0.07	3	0.69	2.41	5	0.71	1.39	7	0.21	0.35
	(0.30)	(0.78)		(0.40)	(0.12)		(0.39)	(0.23)		(0.64)	(0.55)
2	2.01	1.95	4	9.58	15.93	6	1.10	0.10	8	9.95	11.69
	(0.15)	(0.16)		(0.00)	(0.00)		(0.29)	(0.74)		(0.00)	(0.00)

Note: *p*-values for F-tests (contemporaneous coefficients are equal) are listed in parentheses below the estimated coefficients.

Table 12: OLS Estimates of Reduced Form Equations of Lyon's Model, Sample Period 2

	Con.	CB	CB lags	CC	CC lags	CD	CD lags	FD	FD lags	Order flow	Order flow lags	$\bar{R}^2$
1	-6.34 (0.55)	1.18 (0.11)	0.83 (0.49)	-0.12 (0.20)	0.09 (0.29)	-0.72 (0.00)	0.77 (0.00)	-0.26 (0.00)	0.03 (0.76)	0.03 (0.05)	-0.02 (0.47)	0.12
2	0.94 (0.87)	-0.38 (0.49)	0.12 (0.20)	-0.01 (0.69)	-0.28 (0.01)	-0.28 (0.05)	-0.11 (0.78)	-0.15 (0.01)	0.11 (0.12)	0.01 (0.72)	0.01 (0.89)	0.13
3	3.64 (0.69)	-1.06 (0.17)	1.82 (0.21)	-0.42 (0.00)	0.07 (0.76)	-0.55 (0.00)	0.06 (0.89)	-0.13 (0.02)	0.03 (0.58)	0.02 (0.15)	-0.05 (0.53)	0.15
4	-5.67 (0.53)	0.58 (0.37)	0.40 (0.68)	-0.26 (0.10)	-0.05 (0.04)	-0.53 (0.00)	0.17 (0.05)	-0.30 (0.00)	-0.01 (0.96)	0.02 (0.20)	0.02 (0.46)	0.12
5	-4.36 (0.49)	-0.31 (0.60)	-0.64 (0.73)	-0.10 (0.07)	-0.06 (0.53)	-0.31 (0.06)	-0.19 (0.17)	0.06 (0.37)	0.01 (0.89)	0.02 (0.05)	0.00 (0.82)	0.02
6	6.56 (0.49)	-0.73 (0.18)	0.01 (0.93)	-0.50 (0.00)	--0.01 (0.29)	-0.67 (0.01)	-0.28 (0.33)	-0.17 (0.00)	0.04 (0.56)	0.00 (0.59)	0.01 (0.52)	0.09
7	7.85 (0.02)	-0.10 (0.82)	-0.43 (0.84)	-0.24 (0.02)	-0.06 (0.87)	-0.13 (0.87)	0.13 (0.15)	-0.23 (0.00)	0.03 (0.93)	0.00 (0.70)	-0.01 (0.32)	0.02
8	0.09 (0.72)	-1.00 (0.00)	-0.00 (0.98)	-0.00 (0.82)	0.01 (0.39)	-0.01 (0.48)	-0.02 (0.35)	0.00 (0.89)	0.00 (0.93)	0.00 (0.42)	-0.00 (0.92)	0.73

Note: *p*-values for *t*-tests (contemporaneous coefficients are zero) and F-tests (lag coefficients are zero) are listed in parentheses below the estimated coefficients.

Table 13: F-Statistics; Reduced Form Equations of Lyon's Model, Sample Period 2

	CB=CC	CB=CD		CB=CC	CB=CD		CB=CC	CB=CD		CB=CC	CB=CD
1	2.97 (0.08)	6.36 (0.01)	3	0.66 (0.41)	0.41 (0.51)	5	0.12 (0.72)	0.00 (0.99)	7	0.05 (0.80)	0.00 (0.97)
2	0.46 (0.49)	0.03 (0.84)	4	1.58 (0.20)	2.88 (0.09)	6	0.16 (0.68)	0.01 (0.91)	8	585.14 (0.00)	590.34 (0.00)

Note: *p*-values for F-tests (contemporaneous coefficients are equal) are listed in parentheses below the estimated coefficients.

Table 14: Significance of Block Exogeneity Tests

	Exchange rate returns						Per cent change in implied volatility					
	FD		**IB**		**Order flow**		**FD**		**IB**		**Order flow**	
	Sample		**Sample**		**Sample**		**Sample**		**Sample**		**Sample**	
	1	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Aggregate	*	*	*	*	*	*	*	*	*	*	*	*
Dealer 1	*	*	*	*	*	*	*	*	*	*	*	*
Dealer 2	*	*	*		*	*	*	*	*		*	*
Dealer 3	*	*	*	*	*	*	*	*	*		*	*
Dealer 4	*	*	*	*	*	*	*	*	*	*	*	*
Dealer 5	*	*	*	*	*	*	*	*	*	*	*	*
Dealer 6	*	*	*	*	*	*	*	*	*		*	*
Dealer 7	*	*	*	*	*	*	*	*	*		*	*
Dealer 8	*		*	*	*	*	*		*	*	*	*

Notes: Likelihood ratio test statistics have a χ^2 distribution with degrees of freedom equal to the number of restrictions placed on the VAR. * indicates a rejection of the null hypothesis of block exogeneity at the 95 per cent level.

Table 15: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	27.57	26.78	26.38	27.67	26.74	27.09	26.37	26.88	26.52
CB	2.35	0.94	1.77	1.15	2.63	1.42	0.56	1.08	0.25
FD	9.66	4.82	5.11	0.81	1.31	1.81	9.26	2.26	0.18
IB	0.14	0.32	0.18	0.62	0.33	1.93	0.04	0.48	0.10
Order flow	0.25	0.87	0.67	1.813	2.11	1.58	0.80	2.51	2.87
Exchange rate returns	60.01	66.24	65.87	67.91	66.85	66.15	62.95	66.75	70.04

Table 16: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	13.26	14.15	13.35	13.99	13.19	13.18	13.33	13.59	13.06
CB	17.82	3.91	2.80	7.50	2.61	6.42	0.94	2.64	0.35
FD	14.78	4.24	15.03	9.86	5.59	0.24	24.63	2.63	0.23
IB	0.53	3.94	0.11	10.33	6.04	0.65	3.02	3.16	0.82
Order flow	3.83	0.15	0.15	0.11	1.22	1.21	0.35	0.90	1.92
Exchange rate returns	49.75	73.57	68.53	58.18	71.32	78.26	57.69	77.05	83.58

Table 17: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	3.80	3.75	3.82	3.80	3.92	3.86	3.97	3.89	3.92
CB	0.74	1.56	0.45	0.85	0.8	0.16	0.44	0.29	0.04
FD	0.05	0.00	0.53	0.66	0.19	0.55	0.91	0.03	0.23
IB	1.16	0.21	0.21	0.16	0.01	1.26	1.20	0.47	0.23
Order flow	0.28	0.10	0.20	0.02	0.25	0.17	0.24	0.07	0.07
Volatility, % change	93.94	94.34	94.76	94.50	94.78	93.98	93.21	95.22	95.48

Table 18: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	0.81	0.68	0.52	0.75	0.51	0.72	0.59	0.75	0.69
CB	1.01	0.64	0.24	1.41	0.06	0.73	0.57	0.28	0.05
FD	1.96	1.21	1.76	1.72	0.65	0.40	0.79	0.87	0.12
IB	1.28	1.06	3.44	1.07	1.93	0.89	0.82	0.39	0.40
Order flow	0.37	0.75	0.59	0.29	1.25	0.98	0.49	0.58	1.08
Volatility, % change	94.53	95.63	93.42	94.73	95.57	96.24	96.72	97.09	97.63

Table 19: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	21.18	13.98	15.72	14.59	17.97	13.37	8.03	5.77	0.31
CB dummy	8.74	13.74	12.43	14.23	11.40	15.13	18.90	22.19	26.47
FD	9.66	4.82	5.11	0.81	1.31	1.81	9.26	2.26	0.18
IB	0.14	0.32	0.18	0.62	0.33	1.93	0.04	0.48	0.10
Order flow	0.25	0.87	0.67	1.81	2.11	1.58	0.80	2.51	2.87
Exchange rate returns	60.01	66.24	65.87	67.91	66.85	66.15	62.95	66.75	70.04

Table 20: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	30.69	12.18	8.62	15.60	8.22	15.82	5.26	7.73	3.39
CB dummy	0.39	5.88	7.53	5.89	7.58	3.78	9.01	8.50	10.02
FD	14.78	4.24	15.03	9.86	5.59	0.24	24.63	2.63	0.23
IB	0.53	3.94	0.11	10.33	6.04	0.65	3.02	3.16	0.82
Order flow	3.83	0.15	0.15	0.11	1.22	1.21	0.35	0.90	1.92
Exchange rate returns	49.75	73.57	68.53	58.18	71.32	78.26	57.69	77.05	83.58

Table 21: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	3.41	4.04	0.42	3.39	3.39	1.41	1.93	0.21	0.07
CB dummy	1.13	1.28	3.85	1.26	1.35	2.60	2.48	3.97	3.89
FD	0.05	0.00	0.53	0.66	0.19	0.55	0.91	0.03	0.23
IB	1.16	0.21	0.21	0.16	0.01	1.26	1.20	0.47	0.23
Order flow	0.28	0.10	0.20	0.02	0.25	0.17	0.24	0.07	0.07
Volatility, % change	93.94	94.34	94.76	94.50	94.78	93.98	93.21	95.22	95.48

Table 22: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	0.37	0.69	0.31	0.67	0.00	0.37	0.63	0.17	0.13
CB dummy	1.45	0.63	0.45	1.49	0.56	1.08	0.53	0.86	0.61
FD	1.96	1.21	1.76	1.72	0.65	0.40	0.79	0.87	0.12
IB	1.28	1.06	3.44	1.07	1.93	0.89	0.82	0.39	0.40
Order flow	0.37	0.75	0.59	0.29	1.25	0.98	0.49	0.58	1.08
Volatility, % change	94.53	95.63	93.42	94.73	95.57	96.24	96.72	97.09	97.63

Table 23: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	27.30	21.48	18.06	19.86	18.29	20.45	10.10	4.67	1.38
FD	12.37	7.83	8.99	2.50	2.88	1.79	14.69	3.99	0.56
IB	0.09	0.27	0.43	0.54	1.13	3.30	0.09	0.85	0.22
Order flow	0.33	1.50	1.44	3.14	4.02	3.01	1.91	5.89	7.70
Exchange rate returns	59.90	68.93	71.07	73.96	73.66	71.44	73.20	84.59	90.15

Table 24: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	14.29	12.26	6.23	15.64	9.47	14.89	7.39	5.95	3.51
FD	22.24	6.63	17.72	12.68	4.66	2.39	26.28	3.48	0.31
IB	0.86	4.34	0.78	10.58	5.58	1.17	3.33	5.77	1.34
Order flow	5.76	0.33	0.32	0.27	1.95	2.19	0.46	1.29	3.34
Exchange rate returns	56.86	76.44	74.96	60.83	78.34	79.35	62.54	83.51	91.80

Table 25: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	5.98	7.89	7.42	6.77	7.08	8.61	3.57	2.73	1.68
FD	0.13	0.50	0.59	0.63	0.40	0.36	1.32	0.15	0.23
IB	0.92	0.23	0.30	0.18	0.21	1.28	1.86	0.82	0.12
Order flow	0.90	0.32	0.61	0.65	0.97	0.79	0.39	0.52	0.49
Volatility, % change	92.07	91.06	91.08	91.77	91.33	88.95	92.86	95.78	97.48

Table 26: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB dummy	1.49	0.64	0.52	0.13	0.66	0.13	1.08	0.10	0.48
FD	1.51	1.41	2.08	2.23	2.06	0.97	1.31	1.09	0.47
IB	1.51	0.82	3.47	1.84	2.34	1.86	1.12	0.86	0.36
Order flow	0.74	0.88	0.52	0.59	1.28	1.23	0.72	0.78	1.41
Volatility, % change	94.74	96.24	93.41	95.21	93.65	95.82	95.78	97.17	97.29

Table 27: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	21.02	13.62	15.24	14.47	17.72	13.07	7.85	5.65	0.27
FD	13.63	7.05	8.43	2.44	1.86	2.72	14.82	4.13	0.19
IB	0.08	0.22	0.39	0.56	0.52	3.60	0.01	0.88	0.14
Order flow	0.30	1.60	1.12	3.26	3.57	3.02	1.81	5.64	7.29
Exchange rate returns	64.97	77.50	74.80	79.26	76.32	77.59	75.51	83.70	92.09

Table 28: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	28.55	12.09	6.91	15.21	7.72	15.05	5.17	7.29	3.19
FD	16.07	4.51	17.07	12.41	4.16	0.21	29.11	2.88	0.21
IB	0.52	4.04	0.09	10.45	7.36	0.58	2.37	4.13	0.29
Order flow	4.31	0.21	0.24	0.12	1.88	1.36	0.34	1.32	2.64
Exchange rate returns	50.52	79.16	75.68	62.08	78.88	82.79	63.08	84.36	93.67

Table 29: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	3.55	4.29	0.61	3.51	3.59	1.72	2.00	0.13	0.34
FD	0.21	0.01	0.09	0.81	0.21	0.71	1.44	0.10	0.25
IB	1.01	0.19	0.10	0.15	0.00	1.20	1.41	0.79	0.18
Order flow	0.21	0.14	0.39	0.04	0.14	0.12	0.11	0.17	0.23
Volatility, % change	95.00	95.35	98.79	95.48	96.04	96.25	95.03	98.81	98.99

Table 30: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CB	0.59	0.86	0.46	0.42	0.04	0.21	0.64	0.19	0.19
FD	1.59	1.31	1.84	2.05	0.09	0.40	0.91	0.77	0.06
IB	1.49	0.92	3.46	0.97	2.06	0.87	0.71	0.40	0.38
Order flow	0.61	0.80	0.67	0.34	1.49	1.24	0.51	0.79	1.29
Volatility, % change	95.69	96.11	93.57	96.22	95.92	97.27	97.23	97.83	98.07

Table 31: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	Agg.	1	2	3	4	5	6	7	8
CC	9.73	5.34	1.21	0.38	3.52	2.47	1.15	1.22	0.19
FD	19.67	10.13	13.08	5.23	2.29	3.01	20.22	3.82	0.11
IB	0.04	0.53	0.83	0.63	1.43	3.39	0.07	0.79	0.16
Order flow	0.36	2.76	1.03	3.73	6.58	4.88	1.98	6.75	7.27
Exchange rate returns	70.15	81.22	83.84	90.01	86.17	86.25	76.57	87.41	92.25

Table 32: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	Agg.	1	2	3	4	5	6	7	8
CC	4.70	5.55	1.26	1.72	0.83	3.56	8.40	4.72	0.74
FD	24.61	4.85	19.10	15.95	4.30	8.25	25.18	3.44	0.15
IB	0.40	4.77	0.16	11.36	7.03	0.63	1.84	3.15	3.48
Order flow	3.84	1.24	0.35	0.14	2.76	2.99	0.17	1.87	2.68
Exchange rate returns	66.44	83.59	79.12	70.81	85.08	92.54	64.39	86.89	92.95

Table 33: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	Agg.	1	2	3	4	5	6	7	8
CC	0.10	0.79	0.13	0.01	0.42	0.03	1.46	0.19	0.08
FD	1.76	0.53	0.12	1.35	0.48	0.88	3.06	0.14	0.23
IB	0.57	0.07	0.13	0.07	0.05	1.34	0.67	0.83	0.15
Order flow	0.67	0.21	0.32	0.08	0.10	0.15	0.09	0.13	0.23
Volatility, % change	96.88	98.38	99.29	98.48	98.95	95.59	94.71	98.69	99.30

Table 34: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	Agg.	1	2	3	4	5	6	7	8
CC	0.10	0.06	0.57	2.33	1.73	0.22	1.11	0.67	0.51
FD	1.72	1.36	1.83	1.40	0.37	0.41	0.62	0.70	0.11
IB	1.53	0.90	2.74	0.62	1.72	0.77	1.09	0.30	0.43
Order flow	1.15	0.77	0.73	0.41	1.50	1.28	0.74	0.76	1.34
Volatility, % change	95.47	96.92	94.11	95.23	94.66	97.31	96.43	97.55	97.60

Table 35: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CD	0.67	0.06	0.63	0.15	2.31	0.56	1.35	0.28	0.00
FD	26.81	13.20	13.69	5.98	2.84	3.95	20.46	4.11	0.21
IB	0.03	0.11	0.85	0.92	1.61	4.63	0.02	0.84	0.18
Order flow	1.33	1.44	0.99	3.11	6.35	3.75	2.01	6.12	7.28
Exchange rate returns	71.14	85.22	83.84	89.22	86.89	87.12	76.16	88.64	92.31

Table 36: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CD	2.71	2.99	0.58	2.97	1.34	3.41	1.65	0.18	2.61
FD	26.46	8.02	20.27	15.45	4.94	0.41	30.73	3.81	0.20
IB	0.24	3.34	0.22	10.38	6.45	1.20	2.14	3.97	3.24
Order flow	4.71	0.31	0.20	0.09	2.48	1.67	0.22	1.57	2.89
Exchange rate returns	65.89	85.34	78.72	71.10	84.79	93.29	65.24	90.76	91.07

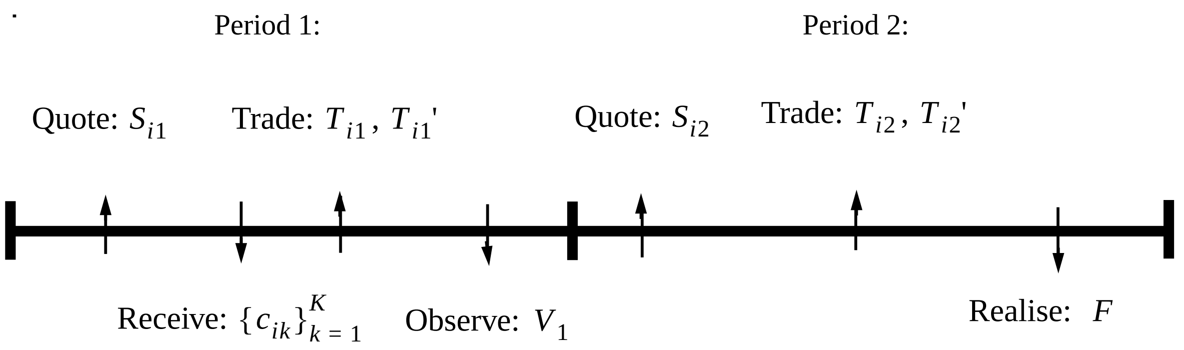
Table 37: Variance Decomposition of Returns, Sample: Jan 1996 to Aug 1998

Intervention period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CD	0.30	0.90	0.04	0.32	0.16	0.03	0.24	0.12	0.01
FD	1.33	0.51	0.13	1.21	0.54	0.89	2.45	0.11	0.28
IB	0.79	0.05	0.08	0.13	0.03	1.33	1.51	0.78	0.14
Order flow	0.41	0.20	0.37	0.05	0.11	0.13	0.13	0.19	0.23
Volatility, % change	97.14	98.34	99.36	98.27	99.16	97.61	95.66	98.81	99.33

Table 38: Variance Decomposition of Returns, Sample: Sep 1998 to Aug 1999

Replenishment period	**Agg.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
CD	0.36	0.03	0.43	0.76	0.42	0.07	5.39	0.71	0.65
FD	1.95	1.38	2.28	1.34	1.41	0.44	1.39	0.74	0.65
IB	1.42	0.79	3.41	1.17	2.01	0.76	0.46	0.31	0.43
Order flow	0.49	0.83	0.63	0.37	1.34	1.22	0.31	0.77	1.41
Volatility, % change	95.77	96.96	93.24	96.35	93.80	97.49	92.49	97.47	97.45

Figure 1: Timing of Simultaneous Trade Model

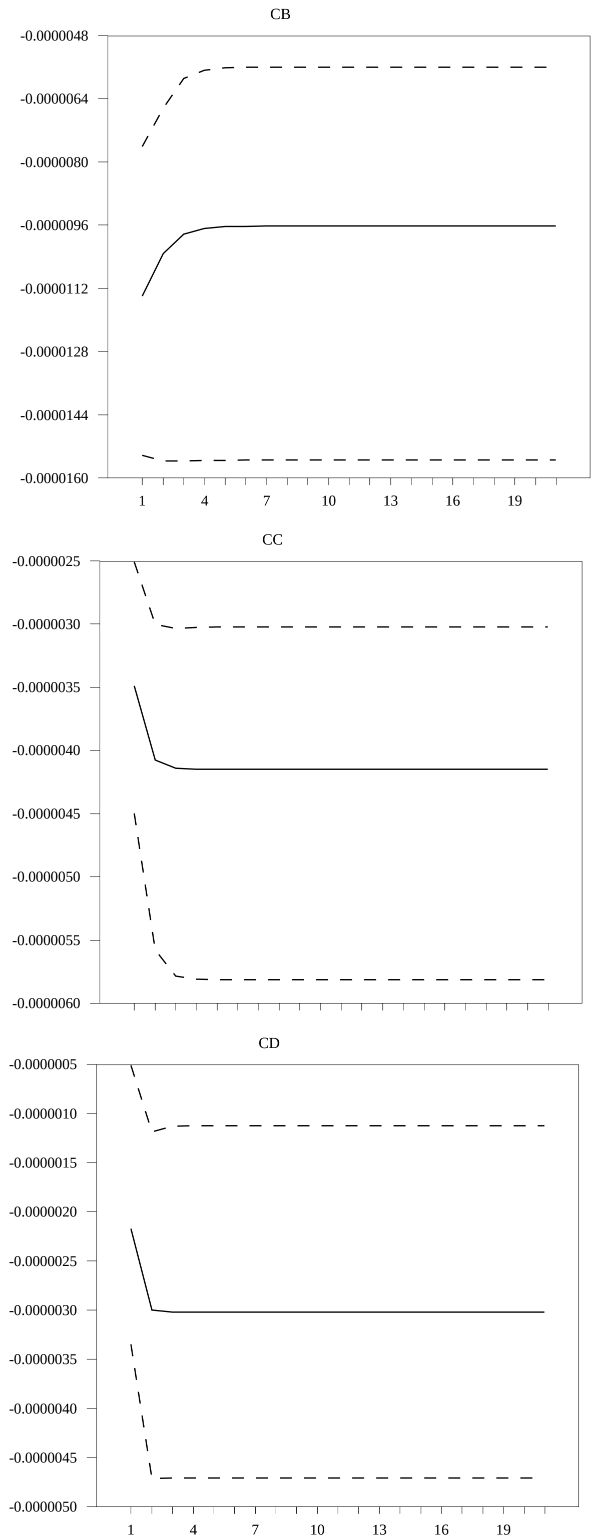


Information sets:

$$\Omega_{T_1} = \{S_{i1}\}_{i=1}^{n} \qquad \Omega_{T_2} = \left\{V_1, \left\{\{S_{ij}\}_{i=1}^{n}\right\}_{j=1}^{2}\right\}$$

$$\Omega_{T_{i1}} = \left\{\{c_{ik}\}_{k=1}^{K}, \{S_{i1}\}_{i=1}^{n}\right\} \qquad \Omega_{T_{i2}} = \left\{V_1, \{c_{ik}\}_{k=1}^{K}, \left\{T_{ij}, T_{ij}', \{S_{ij}\}_{i=1}^{n}\right\}_{j=1}^{2}\right\}$$

Figure 2: Cumulative Change in Exchange Rate Returns, Sample Period 1[15]



15. A sequence of residuals from the estimated VAR are bootstrapped (100 times) to simulate 95 per cent Runcle-style error bands for the impulse response functions are shown in Figures 2 to 5.

Figure 3: Cumulative Change in Exchange Rate Returns in Response to Aggregate Shocks, Period 2

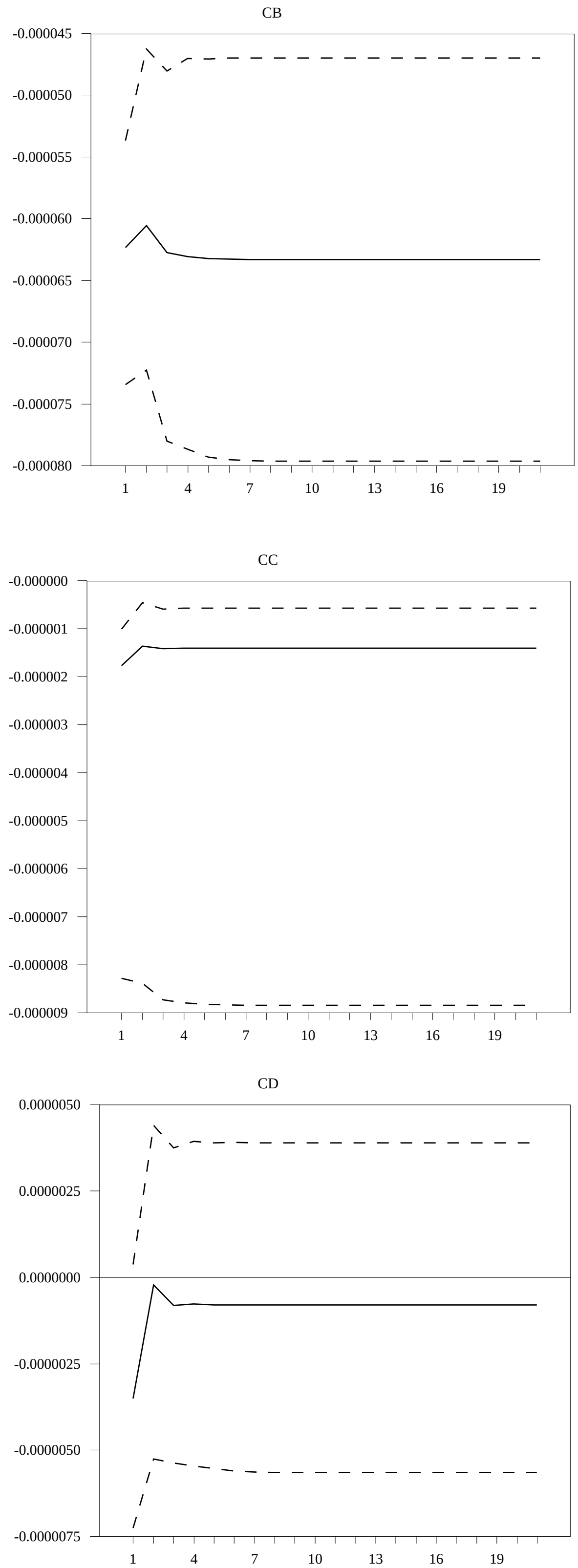


Figure 4: Cumulative % Change in Volatility in Response to Aggregate Shocks, Sample Period 1

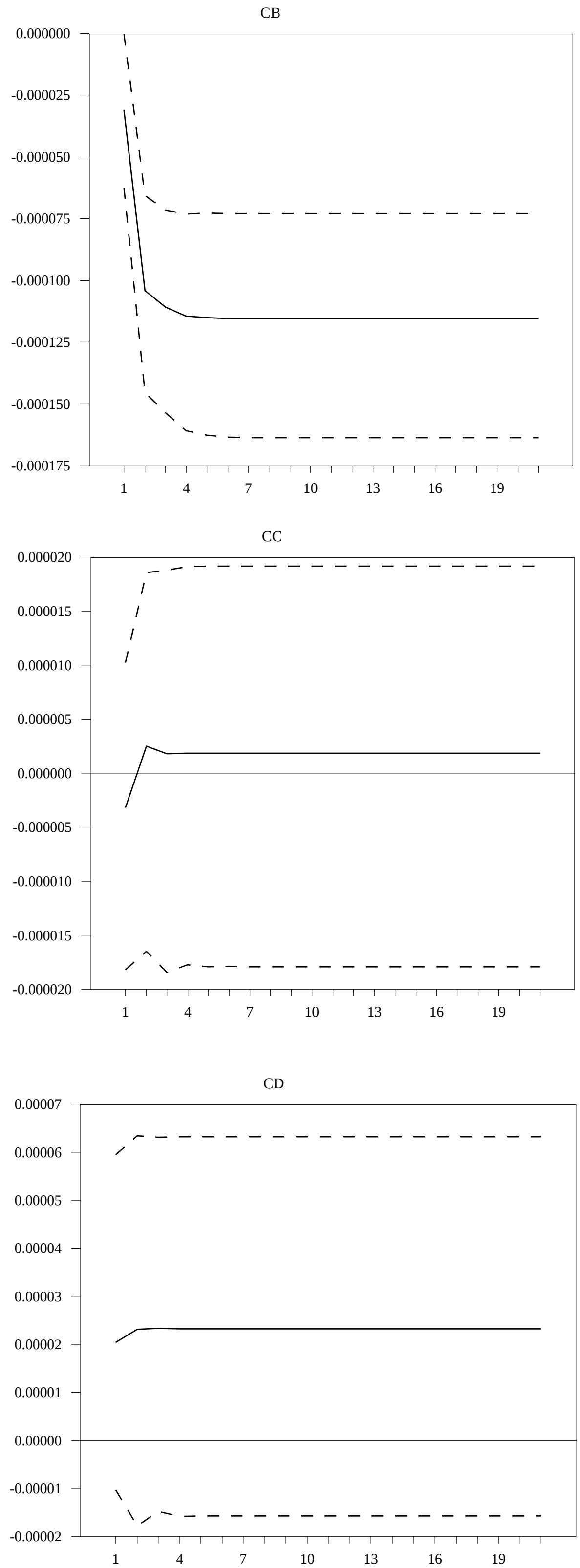
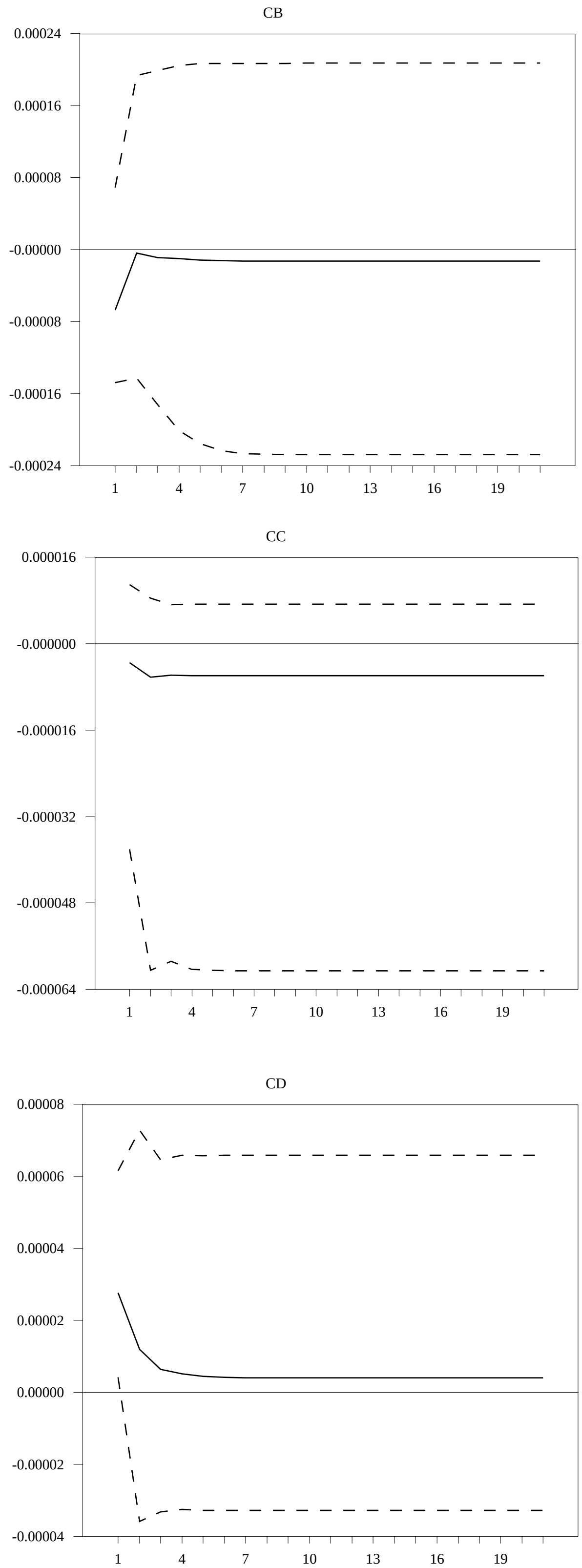


Figure 5: Cumulative % Change in Volatility in Response to Aggregate Shocks, Sample Period 2



Appendix A

A.1 Foreign Exchange Intervention in Canada

In Canada, recent intervention policy has sought to reduce the short-term volatility of the Can$/US$ exchange rate. Uncertainty among market participants about the future stance of monetary policy and extrapolative expectations of chartists are two possible causes of excessive volatility (see Djoudad et al. 2001).

There are a number of mechanisms through which intervention by the Bank can affect the exchange rate. First, a change in the composition of the outstanding stock of domestic and foreign assets may induce investors to adjust their portfolios.[1] This rebalancing of portfolios will affect the demand for foreign and domestic currencies and require an adjustment in the exchange rate. Second, providing additional liquidity to the market when trading activity is thin, usually during periods of market uncertainty, helps to ensure that the FX market operates efficiently and prevents large swings in the exchange rate. Third, by *altering* the technical outlook for the currency, the Bank can avoid the emergence of extrapolative expectations amongst chartists that can generate rapid movements in the exchange rate. Fourth, intervention activities can also convey information about the current or future course of domestic monetary policy. This signal, if credible, may reduce market uncertainty and excessive exchange rate volatility.

On 12 April 1995, the Bank adjusted its intervention program guidelines. Dollar sums used for intervention were raised, “non-intervention exchange rate bands” or target zones were widened, and it was decided that non-intervention bands would be rebased automatically at the end of each business day. Officially, the purpose of these new guidelines was to make intervention more effective at reducing exchange rate volatility and more consistent with maintaining orderly markets.[2] Canadian authorities also decomposed the intervention program into two components, one mechanical and the other discretionary. The aim of this hybrid program was to promote an orderly market by leaning against the prevailing exchange rate trend while providing greater flexibility for authorities to intervene. By late 1998, authorities had dropped mechanical intervention, leaving only discretionary intervention. With the exception of a coordinated effort by the Bank of Japan, U.S. Federal Reserve, Bank of England, European Central Bank, and Bank of Canada to defend the euro in September 2000, the Bank of Canada has not intervened since

1. Intervention is usually sterilized, having no effect on the monetary base, but only a change in the relative composition of Government of Canada domestic and foreign assets.
2. Krugman (1991) develops a model that demonstrates how the expectation of central bank intervention affects exchange rate behaviour within a target zone.

1998 and all recent purchases of foreign currencies are only replenishments of foreign currency reserves.

In a regression model, Murray, Zelmer, and McManus (1997) test whether Canadian FX intervention lessened volatility[3] of the Can$/US$ exchange rate over the period 2 January 1992 to 30 June 1996. This period overlaps both old and new intervention programs. The authors use daily data on intervention levels and exchange rate volatilities in their analysis. A number of macroeconomic and financial time-series variables are included in the analysis to control for the effects of macroeconomic announcements and changing economic conditions on exchange rate volatility. The intervention data is divided into three subcategories: expected intervention, unexpected light intervention, and unexpected heavy intervention. Unexpected, or discretionary intervention, occurs when the Bank rebases its non-intervention bands to make intervention more likely in one direction. Although not officially revealed, details of the new and old intervention programs are assumed to be known to market participants. Under the old program guidelines, none of the intervention variables were found to be significant. After the new intervention guidelines were introduced, unexpected heavy intervention was slightly effective at stabilizing the exchange rate. Murray, Zelmer, and McManus also find that intervention that was anticipated by the market failed to reduce the volatility of the Can$/US$ exchange rate under both old and new programs.

Beattie and Fillion (1999) also test the effectiveness of Canada's FX intervention program, but make one major change in methodology: they investigate whether high-frequency data are better able to capture the effect of intervention on volatility. A 2-1/2-year sample of 10-minute data is accumulated from 12 April 1995 to 30 January 1998. The time span of the data falls exclusively on the period after the new intervention guidelines were introduced.

The estimated equations in the model explain volatility[4] in terms of four factors: intraday seasonal patterns, daily volatility persistence, macroeconomic news announcements, and the impact of intervention. Controlling for the systematic everyday patterns in the nominal exchange rate is extremely important if valid inferences are to be made about the effectiveness of intervention. In general, macroeconomic news announcements are included in the analysis, because they are capable of generating large surprises in the market.

3. Implied volatility, calculated from options market data, is employed as a measure of expected volatility.

4. Volatility in Beattie and Fillion (1999) is estimated using a GARCH (generalized autoregressive conditional heteroscedasticity) methodology.

As in the previous study, Beattie and Fillion find that expected intervention had no direct impact on volatility while discretionary unexpected intervention did reduce exchange rate volatility. Furthermore, over a short period of time, repeated unexpected intervention in the market was effective.

In theory, non-intervention bands should have a stabilizing effect on the exchange rate if the bands are credible and defendable. Consider the special case of a fixed exchange rate: a non-intervention band with equal upper and lower bounds. If the fixed exchange rate is credible and defended by the monetary authority, there will be no variability in the exchange rate. The regression analysis of Beattie and Fillion, however, indicates that intervention bands were only marginally stabilizing.

In general, both papers reach the same conclusion: non-discretionary intervention has no effect on volatility, while discretionary intervention can have a *small* influence. If intervention is consistent with the underlying fundamentals of the economy, volatility of the exchange rate may be reduced if any uncertainty is resolved. On the other hand, if intervention is not credible or has multiple objectives, it only creates confusion in the market.

A.2 Simultaneous Interdealer Trading Model

The following model is based on Lyons' (1997) simultaneous trade model of the FX "hot potato." Although customer trades drive interdealer trading, it is the subsequent multiple periods of interdealer trading that provide real insight into the dynamics of the FX market. The model includes n dealers who behave strategically and a large number of competitive customers who are assigned to those dealers. All dealers have an identical negative exponential utility defined over terminal wealth. After an initial round of customer-dealer trades, there are two rounds of interdealer trading. The interdealer trading rounds correspond to the two periods of the models. A key feature of the model is that trading within a period occurs simultaneously. Simultaneous trading has the effect of constraining dealers' conditioning information: within any period, dealers cannot condition on that period's realization of others' trades. Constraining conditioning information in this way allows dealers to trade on information before it is reflected in price.

There are two assets: one riskless and one risky. The payoff on the risky asset is realized after the second round of interdealer trading, with the gross return on the riskless asset normalized to one. The risky asset is initially in zero supply and has a payoff of F, where $F \sim N(\bar{F}, \sigma_F^2)$.

The seven events of the model occur in the following sequence (see Figure 1):

Period one:

1. Dealers quote.
2. Customers trade with dealers.
3. Dealers trade with dealers.
4. Interdealer order flow is observed.

Period two:

5. Dealers quote.
6. Dealers trade with dealers.
7. Payoff F is realized.

A.2.1 Customer trades

Customer market orders are not independent of the payoff to the risky asset, F. They occur in period one only, and are cleared at the receiving dealer's period-one quote, S_{it}. Unlike the Lyons (1999) model, there are a number of customer "types." For example, commercial clients, non-dealer financial institutions, and central banks are all customers of dealers in the FX market. Each customer trade is assigned to a single dealer, resulting from a bilateral customer relationship. The net type-k customer order (central bank, commercial client, etc.) received by a dealer i is

$$c_{ik} = F + \varepsilon_{ik} \qquad \varepsilon_{ik} \sim N(0, \sigma_{ik}) \qquad \forall k = 1 \ldots K. \tag{19}$$

c_{ik} is positive for net customer sales and negative for net purchases. Customer trades provide a noisy signal about the unobserved payoff to the risky asset. Customer trades, c_{ik}, are not observed by other dealers. They are private information in the model. In the FX market, dealers have no direct information about other banks' customer trades.

A.2.2 Quoting rules

In both periods, the first event is dealer quoting. Let S_{it} denote the quote of dealer i in period t. The rules governing dealer quotes are:

1. Quoting is simultaneous, independent, and required.
2. Quotes are observable and available to all participants.
3. Each quote is a single price at which the dealer agrees to buy and sell any amount.

Simultaneous moves in the FX market, for example, occur through electronic dealing products that allow simultaneous quotes and simultaneous trades. The key implication of rule 1 is that S_{it} cannot be conditioned on S_{jt}. The rule that specifies that quotes are required is consistent with the fact that in actual multiple-dealer markets, refusing to quote violates an implicit contract of reciprocal immediacy and can be punished by reciprocating with refusals in the future. Rule 2 implies that there is a costless search to find the best quote, while the last rule prevents a dealer from exiting the game at times of informational disadvantage.

A.2.3 Interdealer trading rules

The model's two-period structure is designed around the interdealer trading that occurs in each period. Let T_{it} denote the net outgoing interdealer order placed by dealer i in period t and let T_{it}' denote the net incoming interdealer order received by dealer i in period t, placed by other dealers. T_{it}' is positive for purchases by other dealers from dealer i. The rules governing interdealer trading are as follows:

4. Trading is simultaneous and independent.
5. Trading with multiple partners is feasible.
6. Trades are directed to the dealer on the left if there are common quotes at which a transaction is desired (dealers are arranged in a circle).

Rule 4 generates a role for T_{it}' in the model because interdealer trading is simultaneous and independent: T_{it} is not conditioned on T_{it}'. This means that T_{it}' is an unavoidable disturbance to dealer i's position in period t that must be carried into the following period.

Consider now the determination of dealer i's outgoing interdealer orders in each period. Letting D_{it} denote dealer i's speculative demand, we have

$$T_{i1} = D_{i1} - \sum_k c_{ik} + E_{i1}T_{i1}', \tag{20}$$

$$T_{i2} = D_{i2} - D_{i1} + T_{i1}' - E_{i1}T_{i1}' + E_{i2}T_{i2}', \tag{21}$$

where $E_{i1}T_{i1}' = E[T_{i1}'|\Omega_{T_{i1}}]$, $\Omega_{T_{i1}}$ denotes dealer i's information set in period *1*, and T_{it}' denotes the net incoming interdealer order received by dealers i in period t. Public and private information sets are defined in Figure 1. The top two sets include publicly available information at the time of interdealer trading in each period. The second two information sets include public and private information available to each dealer i just before interdealer trading in that period.

Notice in (20) that when dealers are determining their outgoing trade, they must consider both their desired amount, D_{it}, determined by private information, and incoming c_{ik}'s and $E_{i1}T_{i1}'$. Trades with customers must be offset in interdealer trading to establish a desired position, D_{it}. Dealers also do their best to offset the incoming dealer order, T_{i1}' (which they cannot know ex ante because of simultaneous trading). In period two, inventory control has four components: three from the realized period-one position and one from the offset of the incoming T_{i2}'.

A.2.4 The last period-one event: interdealer order flow observed

An additional element of transparency in the model is provided at the close of period one to all dealers. Period-one interdealer order flow, V_1, is observed:

$$V_1 = \sum_{i=1}^{n} T_{i1}. \tag{22}$$

The sum over all interdealer trades, T_{i1}, is net interdealer demand—the difference in buy and sell orders. In FX markets, V_1 is the information on interdealer order flow provided by interdealer brokers.

A.2.5 Dealer objectives and information sets

Each dealer determines quotes and speculative demand by maximizing a negative exponential utility function defined over terminal wealth. Letting W_{it} denote the end-of-period t wealth of dealer i, we have

$$\underset{\{S_{ij}, T_{ij}\}_{j=1}^{2}}{Max} E_i[-\exp(-\theta W_{iFinal})], \qquad (23)$$

subject to

$$\begin{aligned} W_{i1} &= W_{i0} + S_{i1}\Big[-\sum_k c_{ik} + T_{i1}'\Big] - S_{i1}'T_{i1} \\ W_{i2} &= W_{i1} + S_{i2}T_{i2}' - S_{i2}'T_{i2} \\ W_{iFinal} &= W_{i2} + F\Big[(T_{i1} - T_{i1}') + (T_{i2} - T_{i2}') + \sum_k c_{ik}\Big], \end{aligned} \qquad (24)$$

or

$$W_{iFinal} = W_{i0} - (S_{i1} - F)\sum_k c_{ik} + \sum_j^2 (S_{ij} - F)T_{ij}' - \sum_j^2 (S_{i1}' - F)T_{i1}. \qquad (25)$$

Equivalently, by substituting (20) and (21) into (25), we can define the problem in terms of desired positions instead of outgoing trades:

$$\underset{\{S_{ij}, D_{ij}\}_{j=1}^{2}}{Max} E_i[-\exp(-\theta W_{iFinal})], \qquad (26)$$

$$\begin{aligned} W_{iFinal} = {} & W_{i0} - (S_{i1} - S_{i1}')\sum_k c_{ik} + (D_{i1} + E_{i1}T_{i1}')(S_{i2}' - S_{i2}) \\ & + (D_{i2} + E_{i2}T_{i1}')(F - S_{i2}') + T_{i1}'(S_{i2}' - S_{i1}) - T_{i2}'(F - S_{i2}). \end{aligned} \qquad (27)$$

A.2.6 Equilibrium quoting strategies

The equilibrium concept used in this paper is that of a perfect Bayesian equilibrium, or PBE. Under PBE, Bayes' rule is used to update beliefs, while strategies are sequentially rational given those beliefs. Quotes must be common to avoid arbitrage under risk aversion and in light of the quoting rules and trading rules discussed above. The actual derivation of the PBE is provided in Lyons (1997). Below, equilibrium quotes and trades are specified, but only intuition is supplied.

$$S_1 = \bar{F}, \tag{28}$$

$$S_2 = \bar{F} + \lambda V_1 \qquad \lambda > 0. \tag{29}$$

Since prices in both periods are common across dealers and conditioned only on public information, the only variable in Ω_{T_2} relevant for determining period two's price is V_1, interdealer order flow from period one. With common prices, the dealer trading rules in each period (equations (20) and (21)) pin down the equilibrium price in each period once conditioned on public information.

Consider the following intuition for why $\lambda > 0$. Each agent knows one component of V_1, specifically their own outgoing interdealer trade, which is a function of period 1 customer orders. A negative observed V_1 means that, on average, T_{j1} is negative—dealers are selling in interdealer trading. This implies that, prior to interdealer trading, customers sold on average. Dealers are long on average in period 2. To clear the market, the expected return on holding FX must be positive to induce dealers to hold this long position, $S_2 < \bar{F}$. The end result is that the negative value of V_1 drives a reduction in price.

A.2.7 Equilibrium trading strategies

The derivation of trading strategies is tedious and the reader should refer to Lyons (1997) for additional information. In summary, the dealer's problem must be framed as a maximization over realizations of the order flow, V_1. Then, because each dealer needs to account for their own impact on V_1, the problem is redefined again, now over a random variable that is independent of a dealer's own actions. In equilibrium,

$$T_{i1} = \sum_k \beta_{1k} c_{ik} \qquad \beta_{1k} < -1 \qquad \forall k. \tag{30}$$

$$T_{i2} = \sum_k \beta_{2k} c_{ik} + \beta_3 T_{i1}' + \beta_4 (S_2 - \bar{F}) + \beta_5 V_1. \tag{31}$$

Suppose that a trader receives a customer order, c_i. If the trader sought only to hedge their risk, they would cover their position and choose $T_{i1} = -c_i$. But suppose that $V_1 = \sum_i T_{i1} < 0$. In that case, on average, all traders want to sell. To compensate for the additional risk of holding on to the asset, prices must fall $S_2 < \bar{F} = S_1$. Knowing this, the agent strategically alters their outgoing order to capitalize on the higher return by choosing $T_{i1} > -c_i$.

A.3 Vector Autoregression Specification

A VAR is a linear specification in which each variable in the model is regressed against lags of all variables. Letting z_t denote the column vector of model variables,

$$z_t = [c_t, FD_t, IB_t, V_t, returns_t], \tag{32}$$

the VAR specification can be written as:

$$z_t = A_1 z_{t-1} + A_2 z_{t-2} + \ldots + A_K z_{t-K} + \nu_t, \tag{33}$$

where the A_i's are coefficient matrices, K is the maximum lag length, and ν_t is a column vector of serially uncorrelated disturbances (the VAR innovations) with variance-covariance matrix Ω. Estimates of VAR coefficients and associated variance-covariance matrices can be obtained from least-squares. Textbook discussions of vector autoregressions and related time-series techniques used in this paper are given in Judge et al. (1988) and Hamilton (1994).

To characterize the behaviour of the model, impulse response functions are usually more useful than the estimated VAR coefficients. Impulse response functions represent the expected future values of the system conditional on an initial VAR disturbance, ν_t, and may be computed recursively from equation (33) as

$$\begin{aligned} E[z_t|\nu_t] &= \nu_t \\ E[z_{t+1}|\nu_t] &= A_1\nu_t = \Phi_1\nu_t \\ E[z_{t+2}|\nu_t] &= (A_1^2 + A_2)\nu_t = \Phi_2\nu_t \\ &\text{etc.} \end{aligned} \tag{34}$$

Φ_i are the impulse coefficient matrices (Hamilton, 318–24). Since most of the variables in the present model are either flows or changes, it is also useful to consider cumulative quantities. The accumulated response function coefficients are the Ψ_i implicitly given by

$$\begin{aligned} E[z_t|\nu_t] &= \nu_t \\ E[z_t + z_{t+1}|\nu_t] &= (1 + \Phi_1)\nu_t = \Psi_1\nu_t \\ E[z_t + z_{t+1} + z_{t+2}|\nu_t] &= (1 + \Phi_1 + \Phi_2)\nu_t = \Psi_2\nu_t \\ &\text{etc.} \end{aligned} \tag{35}$$

The accumulated response coefficients are continuous functions of the VAR coefficients: $\Psi_i = \Psi_i(A_1, A_2, \ldots)$.

An important component of the accumulated response function is the long-run impact of an innovation on the cumulative (log exchange rate) return. This quantity measures the payoff-relevant information content of the innovation. While microstructure effects may lead to transient effects on cumulative returns, any persistent impact will reflect new payoff information. In terms of the accumulated response coefficient, the cumulative return implied by a particular disturbance may be written as:

$$E[r_t + r_{t+1} + \ldots | \nu_t] = \Psi_{\infty, r} \nu_t, \tag{36}$$

where $\Psi_{\infty, r}$ is the row of the Ψ_∞ matrix that corresponds to the log exchange rate return (the last row is z_t, as defined above). If the VAR representation is invertible (a condition that holds for the present estimations), this may be estimated by $\Psi_{n, r}$ where n is large enough to approximate convergence.

In the present work, hypothetical initial disturbances will be used to study the impact of particular market events. The VAR disturbance may be written as $v_t = Bu_t$, where u_t is a (5×1) column vector of mutually uncorrelated structural disturbances with the property that $Var(u_{i,t}) = Var(u_{j,t})$ and B is a lower-triangular matrix with ones on the diagonal computed by factoring the VAR disturbance covariance matrix Ω, subject to the desired ordering of the variables. This is equivalent to modifying equation (33) to include a contemporaneous term

$$z_t = A_0 z_t + A_1 z_{t-1} + A_2 z_{t-2} + \ldots + A_K z_{t-K} + \nu_t, \tag{37}$$

where the A_0 coefficient is lower triangular.

One hypothesis tested in this paper is whether the various trade flows have similar impacts on exchange rate returns. The hypothesis is tested by comparing the average price impact implied by the impulse response functions corresponding to different trade flow innovations. For ease of interpretation, the total size of each innovation is Can$1 million.

In addition to assessing the effect of particular innovations, it is also of interest to consider broader summary measures of the information contained in these trade flows. Intuitively, the left-hand side of (37) represents the impact of the innovation on the exchange rate net of any transient microstructure effects. The variance of this term is approximately equal to the return variance per unit time, with the return computed over an interval long enough that transient effects can be neglected. Alternatively, the variance term is the variance of the random-walk component implicit in a security price, like the exchange rate, that behaves like a martingale:

$$S_t = S_{t-1} + w_t, \tag{38}$$

where w_t, the unforecastable increment, has the following properties: $Ew_t = 0$, $Ew_t^2 = \sigma_w^2$, and $Ew_t w_\tau = 0 \forall t \neq \tau$. This connection is developed more formally in Hasbrouck (1991b). Denoting this random-walk component as w_t, its variance can be computed from (37) as

$$\sigma_w^2 = var(E[r_t + r_{t+1} + \ldots | \nu_t]) = \Psi_{\infty, r} \Omega \Psi_{\infty, r}'. \tag{39}$$

Since the disturbance covariance matrix will not generally be diagonal, the right-hand side of (39) will typically involve terms reflecting the contemporaneous interaction of the disturbances. Thus, it is not generally possible to identify a component of σ_w^2 that measures the contribution of each type of innovation.

In standard regression analysis, however, the incremental explanatory power of model variables may be measured by adding these variables sequentially to the specification. The incremental explanatory power of a variable derives from its residual (after linearly projecting it onto the variables that preceded it in the specification). This assumption of a particular ordering for the addition of model variables in the general regression case is formally equivalent to the assumption of a particular ordering of contemporaneous effects in the present model.

In the discussion of structural innovations, the assumption was that central bank trade innovations (CB), commercial client trade flow innovations (CC), and Canadian domiciled investment flow (CD) are determined first, followed by foreign domiciled investment flow (FD), marketwide order flow, and return disturbances. This effectively diagonalizes Ω in (39), and the variance of the random-walk component of the exchange rate can be written as:

$$\sigma_w^2 = \sigma_{w,c}^2 + \sigma_{w,FD}^2 + \sigma_{w,IB}^2 + \sigma_{w,V}^2 + \sigma_{w,returns}^2. \tag{40}$$

Each variance on the right-hand side reflects an incremental contribution relative to the variables that precede it in the ordering. $\sigma_{w,c}^2$ is the component of the variance explained by central bank trade flows (CB), commercial client trade flows (CC), or Canadian domiciled investment flows (CD); $\sigma_{w,FD}^2$ is the incremental contribution to foreign domiciled trade flows, etc. To highlight the relative contributions, these values will be reported in proportional form, normalized by σ_w^2,

$$1 = R^2_{w,c} + R^2_{w,FD} + R^2_{w,IB} + R^2_{w,V} + R^2_{w,returns}, \quad (41)$$

where $R^2_{w,c} = \sigma^2_{w,c} / \sigma^2_w$, etc.

Although VARs are commonly used to characterize dynamic models, this approach also has limitations stemming from time aggregation, which leads to co-determined model disturbances and the consequent necessity of identification restrictions. The underlying economic model is based in continuous time. Although trades are discrete events, they can occur at any time. In principle, it would be necessary to specify a sampling interval fine enough to virtually preclude the simultaneous occurrence of events, and so minimize the problems of contemporaneous endogeneity. In practice, however, the time grid is dictated by the data availability.

To summarize, the VAR provides a tractable and comprehensive specification that is capable of capturing the dynamic relations among trade flows and exchange rate returns. Impulse response analysis is one useful way of characterizing a VAR in the present analysis, by constructing the implied price changes associated with the various types of trade flows. A second characterization of the exchange rate return specification in the VAR involves decomposing the sources of (long-run) return variation among the variables. Since returns are ultimately driven by changes in information, these analyses are useful in attributing information effects and the channels through which they operate.

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