FX Trading . . . LIVE!
Dealer Behavior and Trading Systems in Foreign Exchange Markets*

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Abstract

The introduction of electronic broker systems in the foreign exchange (FX) market at the end of 1992 changed the structure of the market and opened new channels for trading. We study the impact of these systems on dealer behavior, using a unique data set on the complete transactions of four FX dealers. We find some support for an information effect in incoming trades conducted directly (bilaterally). For trades executed by electronic broker systems we find no information effects, but we find that sequences of trades in cumulative flow may be infomative for prices. The new electronic systems have changed how dealers control their inventories by introducing new channels for this purpose. Dealers use outgoing trades on electronic brokers to control inventory. Comparing our results to previous research indicates that the introduction of electronic brokers have changed the behavior of dealers.

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1 Introduction

Empirical work on foreign exchange market microstructure is still in its infancy. So far, most microstructure research in foreign exchange spot markets rely on indicative quotes from Reuters FXFX (Goodhart and Figliuoli (1991) and Bollerslev and Domowitz (1993), among others). These data make it possible to address important microstructure issues regarding bid and ask spread, volatility and heterogeneity issues. However, these data do not allow direct testing of dealer behavior since they provide no direct measures of quantity or dealer inventories. This information is the property of the banks, and is regarded as confidential information. The study by Lyons (1995) represents the first attempt to use proprietary inventory and transaction data, covering one dealer for one week in august 1992. Lyons found strong support for the two main microstructural models, inventory control (e.g. Garman (1976), Amihud and Mendelson (1980) and Ho and Stoll (1981)) and information protection (e.g. Kyle (1985), Glosten and Milgrom (1985) and Admati and Pfleiderer (1988)).

The introduction of the electronic brokers at the end of 1992 has changed the structure of the foreign exchange markets. In 1992, interbank trading volume were equally split between direct bilateral trades and traditional voice-broker trades (Cheung and Chinn, 1999; Cheung, Chinn, and Marsh, 2000). However, the market share of the electronic brokers has increased rapidly, and Cheung and Chinn (1999) and Cheung et al. (2000) estimate their share to roughly 50% of interbank trading. Now, direct bilateral trading constitute 35% of total interbank trading, while traditional voice-broker trading constitutes only 15% of total interbank trading. Compared with traditional voice-brokers, the electronic brokers offer higher execution speed and competitive quotes.

There are reasons to believe that the results of Lyons may not hold under this new microstructure. First, the introduction of the electronic brokers has most likely led to increased transparency. The electronic brokers let the dealers see the price and direction of the last trades. Second, the electronic brokers have introduced new channels for trading, hence making it easier to do inventory control.

In this paper we study dealer behavior using a unique data set on the complete trading of four foreign exchange dealers during one week in March 1998.[1] The foreign exchange market, with its decentralized multiple dealer structure offers trading options not available in other financial markets, and not previously studied together. The novel part of our data set is detailed information on what systems (and options) dealers use for trading, which enables such a study. We find that the different system characteristics indeed induce the dealers to behave differently in trading on the different systems.

Microstructural studies of financial markets have had great success during the last decade. It is unfortunate that the foreign exchange market not to the same degree has benefitted from this research. This is a market of great importance that we, despite extensive research, still are not close to having any satisfactory understanding of.[2] Furthermore, the foreign exchange market is very well suited for microstructural studies, maybe to the contrary to the received belief that the foreign exchange market is the most efficient financial market. Market microstructure theory opens for that (i) agents are heterogenous, (ii) information is imper-

[1] The exact period and the name of the bank will be confidential until the final version of the paper.

[2] Since the float of the major currencies in the 1970s, there is in fact little evidence that macroeconomic models have any predictive power (see Meese and Rogoff, 1983a,b; de Vries, 1994).

fect, and (*iii*) that the organization of trading is of importance (Lyons, 1998; Frankel, Galli, and Giovannini, 1996). These are important characteristics of the foreign exchange market.

The heterogeneity of foreign exchange dealers is well established. A questionnaire study of London based foreign exchange analysts by Allen and Taylor (1990) showed considerable heterogeneity of expectations. The studies of Cheung and Wong (2000), Lui and Mole (1998) and Menkhoff (1998) confirm the view of agent heterogeneity. The data in Bjønnes and Rime (2000) shows that dealers expect that other dealers have different information. And we believe that this study is evidence that the trading mechanism in the foreign exchange market is not inconsequential.

In empirical studies of dealer behavior one usually seeks to test the two canonical microstructural theories; the *inventory* approach and the *information* approach. Inventory control models (e.g. Garman (1976), Amihud and Mendelson (1980) and Ho and Stoll (1981)) focus on how risk-averse dealers adjust prices to control their inventory of an asset. The idea is that a dealer with a larger inventory of the currency than desired, will set a lower price to attract buyers. This is called "quote shading." Thus, the spread arises as a price to compensate the Market Maker for not being able to hold the preferred portfolio. Information-based models (e.g. Kyle (1985), Glosten and Milgrom (1985) and Admati and Pfleiderer (1988)) consider adverse selection problems when some dealers have private information.[3] When dealers receive trades, they revise their expectations (upwards in case of a buy order, and downwards in case of a sell order) and set spreads to protect themselves against informed traders.

The main contribution of this paper arises from its high quality data. The data set chronicles the complete trading activity of four different spot dealers during a week in March 1998. As far as we know, only two previous studies use similar data sets, the previously mentioned paper by Lyons (1995), and Yao (1998). Each study a single dealer. Hence, this paper increases the number of foreign exchange dealers studied from two to six, and highlights the diversity of trading styles in the foreign exchange market. Compared to the the data sets of Lyons and Yao, ours is more detailed and accurate. For instance, we can more often determine which dealer was initiating the trade. Our data is also updated on the new microstructure of foreign exchange, and covers the new electronic broker systems. The data of Lyons are from 1992 when electronic brokers had not yet been introduced, and the data of Yao are from 1995 during the introductory phase of the electronic brokers. Thus in this sense they are referring to an outdated microstructure.

To study dealers' pricing behavior we use the model by Madhavan and Smidt (1991). Both Lyons (1995) and Yao (1998) apply this model. The model, originally tailored for the specialist structure at the New York Stock Exchange, incorporates inventory and information effects through two postulated equations. In addition, we study the outgoing trades of the dealers, i.e. trading at other dealers' quotes. This kind of trading is very important in the foreign exchange market, and has not been studied before.[4] Dealers claim that "inventory control is the name of the game in FX". The dealer can control his inventory position by

[3] The first to bring in asymmetric information was Bagehot (1971). In a short paper, writing under pseudonym, Bagehot distinguished between informed and uninformed traders. The market maker always loses to better informed dealers because they will only trade when they win. In order to stay in business the market maker must make at least as much from uninformed dealers as he loses to the informed dealers. These gains arise from the bid-ask spread. The spread may therefore be seen as an information cost.

[4] Lyons and Yao address the importance of outgoing trades, by including them in a test for incoming trades. Hence, they do not test the outgoing trades directly.

"quote shading" in incoming trades or by trading at other dealers' quotes in outgoing trades.

Our results indicate that there are differences in informativeness in the different trading systems. In direct trading (on the electronic systems Reuters D2000-1) we find evidence of an information effect, while there is no information effect in indirect trading (through the electronic broker system Reuters D2000-2 and EBS). A weaker information effect on the electronic brokers are in line with the view that these have led to increased transparency. When it comes to inventory effects the results are more ambiguous concerning incoming trades. There is indication that two of the dealers use incoming trades for inventory control. Inventory control through outgoing trades on the electronic brokers seems to be the preferred channel. Weak inventory effects can be due more options available for this purpose, making it easier and less costly to adjust inventory. Overall, the new microstructure has made the Madhavan and Smidt framework less suitable for foreign exchange markets than what was the case when Lyons performed his study.

The rest of the paper is organized as follows. Section 2 provides some market characteristics and describes the data more closely. We give a detailed description of the trading systems used by foreign exchange dealers. In section 3 we present the Madhavan and Smidt model. Section 4 presents estimation method and results. Also, we derive our extensions, incorporating different trading systems and outgoing trades in this section. The paper ends with conclusions and a discussion for future research (Section 5). All details about derivations are shown in the appendix.

2 Data and Market

The data set employed in this study consists of complete trading records for four spot dealers over a five day period in March 1998. All dealers work in the same Scandinavian commercial bank. The bank is a major player in the foreign exchange market with an long history with foreign exchange trading. The bank say it is are among the 16 largest participants in the world on volume, and among the ten largest on the electronic broker system EBS. The spot market is regarded as the most important part of the foreign exchange market. The spot market share of the average daily turnover of USD 1.5 trillion is about 40%, that is, USD 600 billion (BIS, 1998). The interbank share of spot trading is 80%. The most important currency pair is DEM/USD with an average daily turnover of USD 140 billion. In comparison, the average daily turnover in NOK/DEM is less than USD one billion.

The data set includes transaction prices, quantities and dealer inventories. Lyons (1995) lists some of the advantages of such a data set over other foreign exchange data alternatives, mostly Reuters indicative quotes (see Bollerslev and Domowitz, 1993). The advantages are that transaction prices better reflects market activity, and that for testing of dealer behavior one need inventory observations. This is especially important when trading intensity is high. Compared with new data sets with transaction prices from electronic trading systems, e.g. Payne (1999), our data set has the advantage that it includes dealer inventories and reflects the dealers' choice between different trading systems. Thus, our data allows a direct test of inventory models and the investigation of trading strategies.

In the next section (2.1) we discuss some important characteristics of the foreign exchange market's microstructure. Then (2.2) we present the microstructure data on the four dealers. The four dealers trade in different currency pairs and represent different trading styles. Dealer 1 is a medium-sized Market Maker in DEM/USD. Dealer 2 is described as a "Nintendo-dealer", that is, he takes open positions only for a very short time in DEM/USD using electronic broker systems as "Nintendo"-game machines. Dealer 3 is the largest Market Maker in NOK/DEM. While the other dealers have only limited customer order flows, Dealer 3 has large customer order flows. A customer is a non-bank firm, for instance a multinational company. Customer order flows are important because they represent the most important source of private information and they usually generate a significant portion of dealer profits (see Yao, 1998).[5] Dealer 4 has much in common with Dealer 2, and trades mainly in DEM/USD. Dealer 2, 3, and 4, trade in several other exchange rates as well, while dealer 1 only trade in DEM/USD.

2.1 Important Market Characteristics

The trading options available to foreign exchange dealers in the interbank market can be summarized in a 2×2 matrix, as shown in figure 1. Dealers can trade directly with another dealer through Reuters D2000-1 or telephone, or indirectly with a broker, either a voice broker[6] or one of the electronic brokers EBS or Reuters D2000-2 (rows). In each trade the dealer can either set a price (quote) at which other can trade (incoming), or the dealer can trade at other dealers quotes (outgoing) (columns).

Figure 1: Trading options

	Incoming (Nonaggressor)	Outgoing (Aggressor)
Direct	Trade at own quotes	Trade at other dealers' quotes
Indirect	Dealer give quote(s) to a broker	Dealer trade at quotes given by a broker

When a dealer trade at another dealer's quote, he is taking the initiative to the trade to the trade and often called the "aggressor".

To control their inventory position or to establish speculative positions, dealers can shade their bids in incoming trades, or they can use outgoing trades. In incoming direct trades, dealers may be afraid of using bid shading since this might signal their position to the contacting dealer, who of course know their identity. This concern is most important for dealers with large customer order flows because other dealers get a signal of their private information. In incoming indirect trades, the identity of your counterparty is unknown. Therefore, we might expect that dealers shade their quotes more in indirect trades. However, in indirect trades the dealer decides when to trade, and most of the time the spread is very small and good for large amounts. Thus, bid shading might not be necessary unless trading very large quantities. This is due to the increasing popularity of electronic broking systems. The advantage with incoming trades is that the dealer can trade at the most favorable side of the bid or the ask, while the advantage with outgoing trades is higher speed of execution.

In addition to that your counterparty is known in a direct trade while he is not in an indirect trade, there are some other noteworthy differences between trading direct and indirect via a broker. First, in a direct

[5] Cao and Lyons (1998) present a theoretical model where private information on customer order flow may be important to forecast future demand or supply pressures. Information on central bank interventions may also be important. Notice that this also is information on future demand and supply.

[6] A voice-broker is a broker that communicates with the dealers through radio-networks. The dealers have small speakers at their desk to hear the quotes, and direct telephone lines to the broker.

trade, it is expected that the contacted dealer gives two-way quotes. In an incoming indirect trade, the dealer decides whether to give two-way quotes (bid and ask) or only one-way quotes (bid or ask). In our sample, the dealers typically only give one-way quotes in indirect trades. Second, in an incoming direct trade there is no timing decision. In an incoming indirect trade, there is obviously a timing decision since the dealer decides when to place quotes to brokers. Third, direct trading is usually preferred over indirect trading when trading large amounts. This is probably so because the initiator can choose counterparties that he knows quotes reasonable prices for such volumes. However, this may (or has already?) change with the increased volume traded on electronic broker systems. Finally, in an indirect trade you may have several counterparties, while you can only have one counterparty in a direct trade. These differences make us believe that brokered trades are less informative than direct trades.

Next, we want to relate the different trading systems to the transparency of the foreign exchange market. An important feature of the foreign exchange market, distinguishing it from stock markets, is the decentralized multiple dealer structure, and the low transparency of trading. Transparency is usually defined as the degree of information dissipation in the market. In the foreign exchange market, all direct trades are unknown except to the two parties in a trade. In indirect trades with voice-brokers, a small subset of the trades are communicated to the market via intercoms. On electronic broker systems all trades are communicated to the dealers in a "trade window". Thus, transparency may increase with the growing popularity of the electronic brokers. Since low transparency indicates that private information may exists in the market, the increased importance of electronic broker systems may decrease the degree of private information. However, well-informed dealers with large customer trades may have incentives to hide their information by trading direct. We expect that private information is easier to exploit in the DEM/USD market than in the NOK/DEM market since the market for NOK/DEM is highly concentrated with only few market makers. Thus, it is very difficult to hide information from a large customer order trade.

Table 1 illustrates the changing market structure over the last few years. The interbank trading is split into three categories: Direct trades, traditional broker trades and electronic broker trades. The "Nature of Business" refers to banks' trading. Customer trading is the main source of demand for currency. The two columns with "Survey Data" are calculated from Cheung and Chinn (1999) and Cheung et al. (2000). These surveys favor customer orders somewhat compared with previous works which has estimated customer orders at around 20% of turnover (see Bank of England, 1998). We calculate similar numbers for our dealers and Lyons' (1995) dealer.

From table 1 we see that both direct trading and especially traditional voice-brokers have lost market shares to electronic broking systems.[7] Except Dealer 3, our dealers rely more heavily on electronic broker systems than the average. Dealer 3's trading is close to the average. Lyons' (1995) dealer is not only very different from our dealers, but is also different from the average dealer in 1992/1993. First, he relies more heavily on direct trading and less heavily on traditional voice brokers than the average. Second, he has no

[7] Since voice-brokers have no access to the electronic brokers, there is also the problem of knowing the prices they compete against. Furthermore, their information advantage from seeing much flow has also decreased making it even harder to give competitive quotes. Dealers have also told us that the market share of the electronic systems is increasing very fast. In DEM/USD (or USD/EUR) the winning electronic broker system seems to be EBS. The liquidity is very high. Sometimes it is possible to trade for amounts of EUR 100 million.

Table 1: FX Transaction Types

	Survey Data Now	Survey Data 5 years ago	Dealer 1	Dealer 2	Dealer 3	Dealer 4	Lyons' Dealer
			Transactions Interbank:				
Direct	34.6 %	47.7 %	6.2 %	0.7 %	39.0 %	0.1 %	66.7 %
Trad. Brokers	16.5 %	48.5 %	11.6 %	0.0 %	13.0 %	0.0 %	33.3 %
El. Brokers	48.8 %	3.9 %	82.2 %	99.3 %	47.9 %	99.9 %	0.0 %
			Nature of Business:				
Interbank	65.7 %	66.9 %	96.6%	100%	71.8%	100%	100%
Customer	34.3 %	33.1 %	3.4%	0.0%	27.2%	0.0%	0.0%

The survey data are from Cheung and Chinn (1999) (USA) and Cheung et al. (2000) (UK). The numbers are not remarkably different in the two surveys, and the reported numbers are calculated as simple averages. The surveys were conducted during 1997 and 1998, respectively. Thus, 5 years ago is 1992 or 1993. "Lyons' Dealer" is from Lyons (1995). His data is from 1992.

customer order. This dealer earns money from the bid and ask spread in the inter-dealer market. This means that the majority of his trades are direct and incoming (80% is incoming). To adjust his inventory position he use bid shading instead of outgoing trades.

In the next section, together with the data description, we also describe the trading systems more detailed.

2.2 Data set

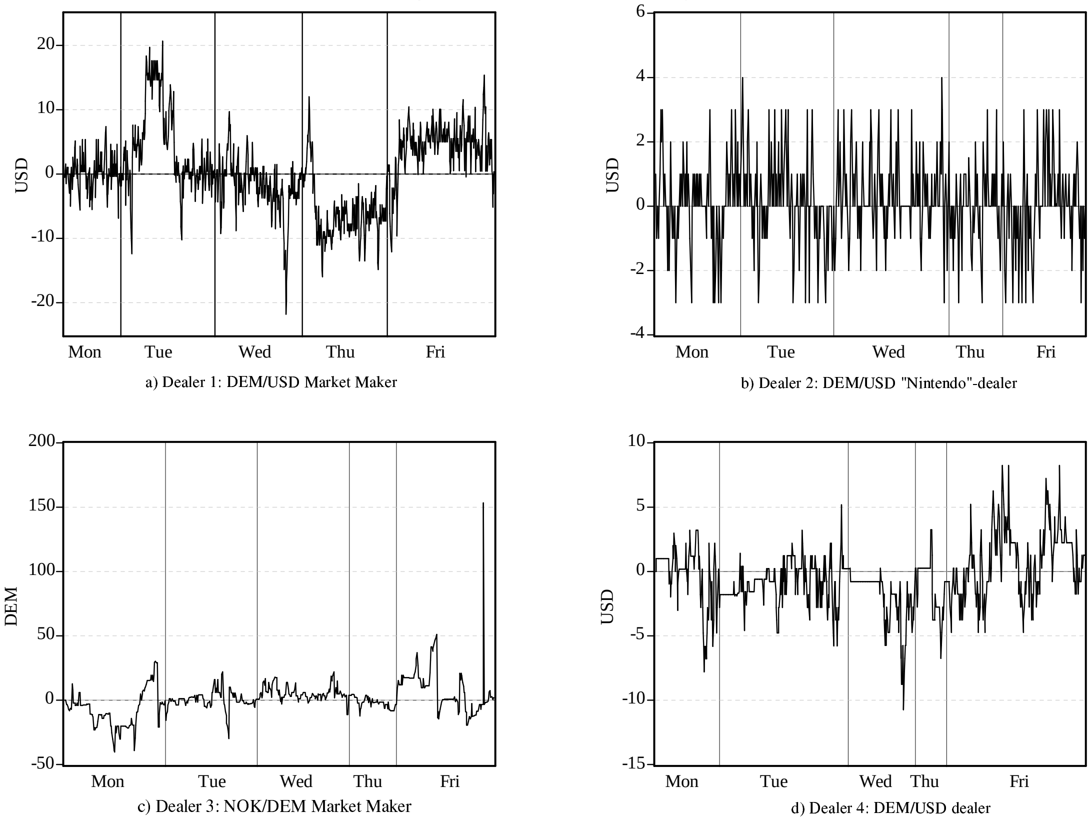
The data set consists of two components: (i) the dealers' record from an internal system used for controlling inventory positions, and (ii) information from electronic trading systems. The matching of the two components and creation of the final data set is described in the appendix.

2.2.1 Inventory positions

The first component of the data set consists of all trades, including trades with "voice" brokers, direct trades completed by telephone, internal trades and customer trades. Trades executed by electronic systems, Reuters D2000-1 and D2000-2, and EBS, are electronically entered into the record. Other trades must be entered manually. A dealer starts the day with his overnight position, and enters his trades during the day. Thus, we can track the dealers' inventory position. The record gives the dealers' information on their inventories and accumulated profits during the day and during the last month. In this part of the data set, we have information on transaction time, transaction price, volume, counterpart and which currency the dealer bought and which he sold.

Figure 2 present inventory positions of the four dealers in the currencies that we are most interested in. There are pronounced differences in the development of dealer inventories during the week. Dealer 1 trades only in DEM/USD. The maximum long dollar position was USD 21 million, the maximum short dollar position USD 22 million. He ends each day with a position close to zero. Dealer 2 has only small open positions. During the week, he never had positions for more than USD 4 million. Still, he earned on average USD 8030 each day. Compared with Dealer 1, the inventory of Dealer 2 shows much less persistence. After initiating an open position, Dealer 2 squares the position in the next trade. Similar to Dealer 1 he ends the day with zero net inventory. Dealer 3 has a maximum long DEM position of DEM 51 million and a maximum short position of DEM 40 million. Dealer 4 has a maximum USD position of USD 8 million and a maximum short position of USD 11 million.

Figure 2: Dealer Inventory



The evolution of dealers inventory over the week. Dealer 1 (panel a), 2 (panel b) and 4s (panel d) inventory are in USD million, while Dealer 3s inventory is in DEM million. The horizontal axis is in"transaction"-time. Vertical lines indicate end of day. The numbers are in USD million.

Except dealer 1, all dealers trade in several currency pairs. While Dealer 2 has only limited trading in other currencies, Dealer 3 and Dealer 4 have significant trading in several European currency crosses. Dealer 3 and Dealer 4 do not necessarily end each day with zero net position. This in contrast to the general opinion that all foreign exchange dealers end the day with a net position close to zero (Lyons, 1995; Yao, 1998). The most likely explanation for this finding is that (i) the volatility in European currency crosses is low and (ii) it is expensive to square the position at the end of the day in less traded currency pairs.

2.2.2 Information from electronic trading systems

The second component of the data set consists of all trades executed on the three electronic trading systems, Reuters Dealing 2000-1, Reuters Dealing 2000-2 and EBS.

Reuters Dealing 2000-1 The Reuters D2000-1 allows dealers to communicate quotes and trades bilaterally via computer rather than verbally over the telephone. There are some advantages by using Reuters D2000-1 compared with using telephone or brokers. First, this system is used for trading in currencies not traded on the electronic broker. Second, it is the only system for trading small or odd quantities, but is also used for trading large quantities. Third, D2000-1 allows dealers to request or handle quotes with four different counterparties simultaneously. Finally, the computerized documentation reduces the paperwork required by the dealers. Our dealers use D2000-1 for most of the direct inter-dealer trades.

From the Reuters D2000-1 system, we have the following information: (i) The time the communication is initiated and ended (to the second), (ii) the name of the counterpart, (iii) who is the aggressor (that is, who is requesting the quote), (iv) the quote quantity, (v) the bid and ask quotes (may also be just bid or ask), and if the conversation results in a trade, (vi) the quantity traded, and (vii) the transaction price.

Figure 3 provides an example of a D2000-1 conversation when a trade takes place. A conversation starts by a dealer contacting another dealer. The contacting dealer usually asks for bid and ask quotes for a certain amount, for instance USD one million.[8] When seeing the quotes, the contacting dealer states whether he wants to buy or sell. In some cases, he may ask for better quotes, or end the conversation without trading. However, most conversations result in a trade. All D2000-1 transactions in the data set take place at the quoted bid or ask.

Figure 3: D2000-1 conversation

```
From ''CODE'' ''FULL NAME HERE'' *0728GMT ????98 */7576
Our Terminal:  ''CODE''       Our user:  ''FULL NAME HERE''
    DEM 1
#   45.47
    BA> I BUY
#   TO CONFIRM AT 1,8147 I SELL 1 MIO USD
#   VAL ??(+2)??98
#   MY DEM TO ''FULL NAME HERE''
#   THANKS AND BYE
    TO CONFIRM AT 1,8147 I BUY 1 MIO USD
    VAL ??(+2)??98
    MY USD TO ''FULL NAME HERE''
    THANKS FOR DEAL FRDS. CHEERS
#
    # END REMOTE #

ˆ   ## TKT EDIT OF CNV 7576 BY ''CODE'' 0728GMT ????98
ˆ   STATUS CONFIRMED
ˆ   ##ENDED AT 07:27 GMT#

(   293 CHARS)
```

An example of a D2000-1 conversation when a trade takes place. The first word means that the call came "From" another dealer. There are information regarding the institution code and the name of the counterpart, and the time (Greenwich Mean), the date, and the number assigned to the communication. DEM 1 means that this is a request for a spot DEM/USD quote for up to USD 1 million, since it is implicitly understood that it is DEM against USD. At line 4, we find the quoted bid and ask price. Only the last two digits of the four decimals are quoted. In this case, the bid quote is 1.8145 and the ask quote is 1.8147. When confirming the transaction, the communication record provides the first three digits. In this case, the calling dealer buys USD 1 million at the price 1.8147. The record confirms the exact price and quantity. The transaction price always equals the bid or the ask. There is also information regarding the settlement bank. "My DEM to "Settlement bank" identifies the settlement bank of "our bank", while "My USD to "Settlement bank" identifies the settlement bank of the other bank. It is usual to end a conversation with standard phrases, such as "thanks and bye," "thanks for deals friends."

D2000-1 allows a dealer to contact a specific other dealer, at the cost of identifying oneself and revealing information to the other dealer. However, for larger trades this system may be more suitable than

[8]In some cases, the contacting dealer also tell whether he wants to buy or sell.

the electronic brokers since a dealer only contacts other dealers that he knows are willing to trade these volumes at reasonable prices.[9] The dealers of both Lyons (1995) and Yao (1998) had so called "10 million"-relationships with several other dealers, meaning that when they contacted each other and did not state a quantity, it was implicitly understood that the request was good for USD 10 million. Dealer 3 has a similar agreement in NOK/DEM.

Electronic broker systems In general the three most important aspects of any kind of foreign exchange broker, traditional "voice" brokers or electronic brokers, are that (*i*) the initiating part stay anonymous, (*ii*) dealers can decrease risk by entering one-way prices (bid or ask) without being worried about revealing their position, and (*iii*) the quoting party choose when to place a quote, opposed to direct trading. The execution is, of course, still decided by the "hitting" dealer.

Electronic broker systems do the same job as humans but at a reduced cost. A bank dealer with access to one of the electronic broker systems can enter his buy and/or sell price into the system as an market maker. D2000-2 and EBS show only the highest bid and the lowest ask, thereby minimizing the spread. These will normally be entered by different banks, but the identity of the inputting bank is not shown. The total quantity that are entered for trade on these quotes is also shown. This means that when more than one bank input the same best bid (ask) price, the quantity shown is the sum of that offered by these banks. This quantity is shown as integers of USD one million, and in some bilateral cases DEM one million. When the quantity is at least ten million, "R" is entered on the D2000-2 screen. EBS shows two set of bid and ask quotes, for amounts up to ten million USD or DEM, and for amounts of at least ten millions. This information is optional on the D2000-2 screen. The limit orders below the best bid and above the best ask, and the respective quantities, are entered and stored in the systems, but not revealed over D2000-2 and EBS. Another bank dealer, possibly in the same bank, can hit the bid or the ask by typing instructions on his own machine.

In our data set, trades executed by electronic broker systems provide almost exactly the same information as the D2000-1 records. The exception is that only the transaction price can be observed, that is, we cannot see the bid and ask spread.[10] However, the spread is tight - very often only one pip (that is, 0.0001 DEM).

2.2.3 The final data set

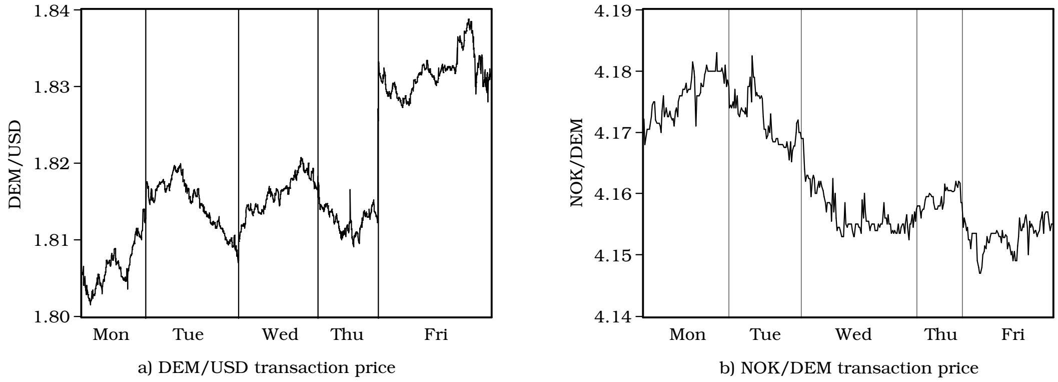
Figures 4 present two plots. The first is the transaction price for DEM/USD over the full sample period, while the second provides transaction prices for NOK/DEM over the full sample period.

Table 2 reports statistics on the dealers' daily activity during the sample period. Dealer 1 has an average daily trading volume of USD 443 million. Dealer 2 averages USD 142 million in DEM/USD. He also has some trading in European currency crosses. Dealer 3's average daily trading volume in NOK/DEM is DEM 292 million. He also trades in other currency pairs. Most important is customer trading in NOK/USD. With

[9] However, this advantage is becoming smaller since the liquidity of the electronic broking systems has become very high.

[10] Another slight difference is that EBS deals are only time stamped in minutes while D2000-1 deals and D2000-2 deals are time stamped in seconds.

Figure 4: Transaction prices



Transaction prices during the week. The source is all the spot transactions conducted electronically by the whole FX department of the bank. The horizontal axis is in "transaction"-time. Vertical lines indicate end of day.

about USD 0.3 billion of the daily trading volume of USD 0.7 billion (43%) (BIS, 1998)[11] in the Norwegian market, he is certainly a major player in this market. Dealer 4 also trades in several currency pairs. Her trading in DEM/USD averages USD 145 million. Trading in SEK/DEM is also important for this dealer. From table 2 we can see that there is considerable daily variation in turnover. For instance, for Dealer 3 the busiest day in NOK/DEM has as much as five times the turnover compared with the most quiet day.

Table 2: Trading volumes and number of trades

			Mon.	Tue.	Wed.	Thu.	Fri.	Total
Dealer 1	DEM/USD	Amount	302	491	464	395	562	2214
		Number	133	221	192	206	240	992
	All trades	Number	133	221	192	206	240	992
Dealer 2	DEM/USD	Amount	138	164	178	82	150	712
		Number	95	99	111	56	91	452
	All trades	Number	104	111	133	67	99	514
Dealer 3	NOK/DEM	Amount	373	304	325	79	377	1458
		Number	73	71	87	31	70	332
	All trades	Number	135	123	127	66	134	585
Dealer 4	DEM/USD	Amount	115	201	82	31	298	727
		Number	64	126	47	18	180	435
	All trades	Number	114	239	129	60	246	788

Total absolute volume traded in the specified exchange rates each day, and the number of trades in the same exchange rates. Dealer 2, Dealer 3 and Dealer 4 trade in several exchange rates. The ones shown in the table are the most important currency pair traded by each dealer. "All trades" represent all trades executed by the dealer.

Tables 3-6 present some statistics about the different types of trades. Dealer 2 and Dealer 4 rely almost exclusively on electronic broker systems when trading DEM/USD. Electronic broker systems are also important for Dealer 1. Electronic broker systems account for 77% of his total volume. Note that most of the outgoing trades are executed by D2000-2, while most of the incoming trades are executed by EBS. The dealers told us that the choice of trading incoming or outgoing at electronic trading systems is related to the fee structure. Dealer 3 also uses electronic broker systems to some extent, but only for 28% of total volume.

[11]This number reflects NOK/DEM trading with at least one Norwegian bank as counterpart. Taking account of some NOK/DEM trading executed outside of Norway the share will be somewhat lower.

The majority of these trades are executed by D2000-2 because there is no active trading in NOK/DEM at EBS. Dealer 1 and Dealer 3 also use traditional voice brokers. For Dealer 1 voice-broker trades account for 11% of total volume, while for Dealer 3 the number is 8%.

Table 3: Descriptive statistics: Dealer 1

	Direct trading		Electronic brokers							
	D2000-1		D2000-2		EBS		Voice		Internal	
	Inc.	Teleph.	Inc.	Out.	Inc.	Out.	broker	Customer	trades	Total
No. of trades	78	1	109	276	250	177	57	23	21	992
– % total	7.9	0.1	11.0	27.8	25.2	17.8	5.7	2.3	2.1	100
Volume	125	5	203	606	456	447	242	72	58.9	2214
– % total	5.6	0.2	9.2	27.4	20.6	20.2	10.9	3.2	2.7	100
Average size	1.6	NA	1.9	2.2	1.8	2.5	4.2	3.1	2.8	
Median size	1.0	NA	1.0	2.0	1.0	2.0	5.0	1.0	2.5	
Stdev.	1.7	NA	1.1	1.3	1.2	1.5	2.0	4.2	2.9	
Min	0.3	NA	1.0	1.0	1.0	1.0	1.5	0.1	0.1	
Max	10.0	NA	5.0	8.0	10.0	9.0	10.0	15.0	10.5	

The table lists different types of trades over the sample period, one week in March 1998. If possible, the trades are separated as incoming (inc.) or outgoing (out.). All dealers use D2000-1 only for incoming trades. All volume numbers are measured in USD. Dealer 1 did only trade in DEM/USD.

Table 4: Descriptive statistics: Dealer 2

	Direct trading		Electronic brokers							
	D2000-1		D2000-2		EBS		Voice		Internal	
	Inc.	Teleph.	Inc.	Out.	Inc.	Out.	broker	Customer	trades	Total
No. of trades	5	0	35	191	151	65	0	0	5	452
– % total	1.1	0.0	7.7	42.3	33.4	14.4	0.0	0.0	1.1	100.0
Volume	5	0	63	316	215	106	0	0	7	712
– % total	0.7	0.0	8.8	44.4	30.2	14.9	0.0	0.0	1.0	100.0
Average size	1.0	NA	1.8	1.7	1.4	1.6	NA	NA	1.4	
Median size	1.0	NA	2.0	1.0	1.0	1.0	NA	NA	1.0	
Stdev.	0.4	NA	0.8	0.9	0.7	0.8	NA	NA	1.1	
Min	0.5	NA	1.0	1.0	1.0	1.0	NA	NA	0.1	
Max	1.5	NA	3.0	5.0	3.0	3.0	NA	NA	3.0	

The table lists different types of trades over the sample period, one week in March 1998. If possible, the trades are separated as incoming (inc.) or outgoing (out.). All dealers use D2000-1 only for incoming trades. All volume numbers are measured in USD. Dealer 2 had 62 trades in other exchange rates than DEM/USD, which is 12.1% of the total number of trades.

Dealer 1 and Dealer 3 use direct trading to some extent, that is, they give quotes on request. They do not use outgoing direct trades since this was regarded as expensive. Dealer 3 was also concerned by not signalling his inventory position. For Dealer 1 direct trading account for less than 10% of total volume, while for Dealer 3 direct trading account for 23% of total volume.

Dealer 2 and Dealer 4 have some customer trading, but not in DEM/USD. For Dealer 1 customer trades account for only 3% of total trading. Customer trading is very important for Dealer 3. About 17% of his trading in NOK/DEM is with customers. Also, he has considerable customer trading in other currency crosses. Most important is NOK/USD.

Dealers use internal trades to adjust their inventory position. Instead of trading in the market, they can trade with another dealer in the same bank. All dealers have some internal trades. Other types of trades,

Table 5: Descriptive statistics: Dealer 3

	Direct trading		Electronic brokers							
	D2000-1		D2000-2		EBS		Voice		Internal	
	Inc.	Teleph.	Inc.	Out.	Inc.	Out.	broker	Customer	trades	Total
No. of trades	90	3	59	46	0	2	16	50	26	292
– % total	27.1	0.9	17.8	13.9	0.0	0.6	4.8	17.1	8.9	100.0
Volume	337	4	223	176	0	20	114	246	227.9	1348
– % total	23.1	0.3	15.3	12.1	0.0	1.4	7.8	18.3	16.9	100
Average size	3.7	1.4	3.8	3.8	NA	10.0	7.1	4.9	8.8	
Median size	0.6	1.5	3.0	3.0	NA	10.0	5.0	3.0	5	
Stdev.	4.9	0.3	2.5	2.5	NA	0.0	2.4	7.7	13.3	
Min	0.0	0.8	1.0	1.0	NA	10.0	4.0	0.0	0.1	
Max	40.0	2.0	20.0	14.0	NA	10.0	15.0	50.0	65	

The table lists different types of trades over the sample period, , one week in March 1998. If possible, the trades are separated as incoming (inc.) or outgoing (out.). All dealers use D2000-1 only for incoming trades. All volume numbers are measured in DEM. Dealer 3 had 253 trades in other exchange rates than NOK/DEM, which is 38.1% of the total number of trades.

Table 6: Descriptive statistics: Dealer 4

	Direct trading		Electronic brokers							
	D2000-1		D2000-2		EBS		Voice		Internal	
	Inc.	Teleph.	Inc.	Out.	Inc.	Out.	broker	Customer	trades	Total
No. of trades	0	1	110	109	168	35	0	0	12	435
– % total	0.0	0.2	25.3	25.1	38.6	8.0	0.0	0.0	2.8	100
Volume	0	1	196	235	227	58	0	0	10	727
– % total	0.0	0.1	27.0	32.3	31.2	8.0	0.0	0.0	1.4	100
Average size	NA	1	1.8	2.2	1.4	1.7	NA	NA	0.8	
Median size	NA	1	2.0	2.0	1.0	2.0	NA	NA	0.5	
Stdev.	NA	NA	0.7	1.0	0.6	0.7	NA	NA	0.4	
Min	NA	1	1.0	1.0	1.0	1.0	NA	NA	0.1	
Max	NA	1	5.0	8.0	5.0	3.0	NA	NA	3.0	

The table lists different types of trades over the sample period, one week in March 1998. If possible, the trades are separated as incoming (inc.) or outgoing (out.). All dealers use D2000-1 only for incoming trades. All volume numbers are measured in USD. Dealer 4 had 353 trades in other exchange rates than DEM/USD, which is 44.8% of the total number of trades. Most important was trading in SEK/DEM.

order and option/hedge, are less important for these dealers. Note, that a foreign exchange dealer may trade in several currency crosses. Except for Dealer 1, all dealers trade in several currency crosses. For instance, Dealer 3 has almost 40% of his trades in other currency crosses than DEM/USD, while Dealer 4 has 45% of the trades in other currency crosses than DEM/USD. Most important is NOK/USD for dealer 3 and SEK/DEM and dealer 4.

3 The model

We use the model of Madhavan and Smidt (1991). Consider a pure exchange economy with a risk free and a risky asset. The risky asset represents currency. There are n dealers, and T periods (the whole trading day). The basic model focus on the pricing decision of a representative dealer i (market maker), so each period is characterized by one incoming order at dealer i's quote. Incoming means that the bilateral contact was initiated by dealer i's counterparty, denoted j (aggressor). So periods are in "trading"- or "transaction"-time, and not in "clock-time". At time T the true value, $\tilde{V}$, of the currency is revealed. The value in period 0 is known and equal to r_0. After trading in period t, there arrives some new public information $r_t \sim IID\left(0, \sigma_r^2\right)$. Private information is short-lived in the sense that when r_t arrives at time t agents know that the true value is described as $V_t = \sum_{\tau=0}^{t} r_\tau$.

Information and inventory effects are incorporated through two postulated behavioral equations:

$$Q_{jt} = \theta\left(\mu_{jt} - P_{it}\right) + X_{jt} \tag{1}$$

$$P_{it} = \mu_{it} - \alpha\left(I_{it} - I_i^*\right) + \gamma D_t. \tag{2}$$

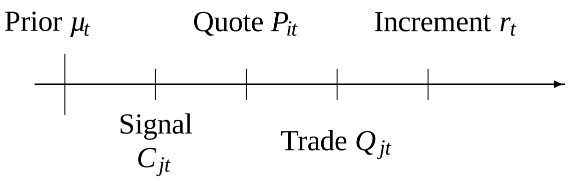
Equation (1) states that the quantity dealer j wants to trade in period t, depends on the difference between his conditional expectation of V_t (μ_{jt}) and i's quote (P_{it}). In addition dealer j's desired trade includes an mean zero stochastic element X_{jt}, which represent inventory-adjustment trading and is uncorrelated with V_t. The demand of the contacting dealer j, (1), is optimal when dealers maximize exponential utility over end-of-period wealth, added.the X_{jt}. If his conditional expectation is above (below) dealer i's quote, he tend buy (sell) dollars. Since X_{jt} is only known to trader j, Q_{jt} only provides a noisy signal to dealer i of V_t. Note that Q_{jt} will be positive for sales to dealer j and negative for purchases.

Equation (2) is a typical inventory model, where price (P_{it}) is linearly related to the dealer's current inventory (I_{it}). I_i^* is i's desired inventory position, and α (> 0) measures the inventory response effect. The effect from inventory is negative because the dealer may want to "shade" (reduce) his price to induce a sale if the inventory is above the preferred level. Dealer i's conditional expectation of V_t is given by μ_{it}. D_t is a direction-dummy that takes the value 1 if it is a sale (trade at the ask) and -1 if it is a buy (trade at the bid), as seen from the Market Maker. Since the quoted spread is expected to widen with quantity to protect against adverse selection, we can think of γD_t as half of the spread for quantities close to zero.

The price is set such that it is ex post regret-free after observing the trade Q_{jt}. Regret-free, in the sense of Glosten and Milgrom (1985), means that conditional on observing the size and the direction of the order, dealer i does not want to change his quote. In reality dealers give both buy and sell prices for a given quantity. If the contacting dealer buys, the bid price reflects the expectation conditional on a buy.

When transparency is low there may exist private information, and this can be modeled through the informational environment. Figure 5 summarizes the information structure, seen from the perspective of dealer i's quoting.[12]

Figure 5: Information structure within period t



At the beginning of each period all information is public and each dealer holds the same prior belief. Before trading in the period dealer j observe a private signal. Then dealer j requests for a quote P_{it} from dealer i. The trade Q_{jt} is then realized. In the end of the period all information is made public, hence private information is only short-lived.

Both dealers' prior belief (μ_t) on the full information value V_t are each period based on public information, such as public news and information on market-wide order flows from voice-brokers or electronic broker systems, and is given by

$$\mu_t = V_t + \tilde{\eta}_t. \tag{3}$$

The noise term, $\tilde{\eta}_t$, is independently normally distributed around zero with variance σ^2_η. Also at the beginning of each period t, dealer j receives a private signal C_{jt} of V_t,

$$\tilde{C}_{jt} = V_t + \tilde{\omega}_{jt}, \tag{4}$$

where the noise term, $\tilde{\omega}_{jt}$, is independently normally distributed around zero with σ^2_ω. The most important source of private information is a customer deal.[13] For dealer i the quantity actually traded with dealer j gives a signal of C_{jt}.

To derive the price-schedule we need to insert for the expectations in (2) and (1). After observing the private signal C_{jt}, dealer j's posterior (μ_{jt}) can be expressed as

$$\mu_{jt} = \lambda\mu_t + (1-\lambda)C_{jt}, \tag{5}$$

where $\lambda = \sigma^2_\omega/(\sigma^2_\eta + \sigma^2_\omega)$ since $\tilde{\eta}_t$ and $\tilde{\omega}_{jt}$ are independent of one another. Dealer i conditions on various possible Q_{jt}'s when setting his prices. More specifically, dealer i forms the sufficient statistic Z_{jt} given by

$$Z_{jt} = \frac{Q_{jt}/\theta + P_{it} - \lambda\mu_t}{1-\lambda} = V_t + \omega_{jt} + \frac{1}{\theta(1-\lambda)}X_{jt}. \tag{6}$$

[12]In the model it is only dealer j that observes a private signal, while the quoting dealer i does not. However, most interbank dealers receive some private signals from customer order flows. A dealer cannot choose when information arrives. Therefore, a Market Maker may have private information while he gives quotes. Bjønnes and Rime (2000) extends the Madhavan and Smidt (1991) model to a situation where both dealer j and dealer i observe a private signal.

[13]Notice, although C_{jt} is a private signal, it is drawn from a common distribution. This is necessary to posit the demand equation in (1) where the θ-parameter is common for all dealers.

Equations (1) and (5) are used to derive the second equality. Z_{jt} is normally distributed with mean V_t and variance σ^2_{Zj} (equal to the variance of the two last terms). Furthermore, Z_{jt} is statistically independent of μ_t. Dealer i's posterior belief (μ_{it}) is a weighted average of μ_t and Z_{jt},

$$\mu_{it} = \kappa\mu_t + (1-\kappa)\, Z_{jt}, \tag{7}$$

where $\kappa = \sigma^2_{Zj}/(\sigma^2_\eta + \sigma^2_{Zj})$. Using the first equality in (6), we see that dealer i's posterior belief is expressed as a function of any Q_{jt},

$$\mu_{it} = \phi\mu_t + (1-\phi)\left(\frac{Q_{jt}}{\theta} + P_{it}\right), \tag{8}$$

where $\phi = \kappa - \lambda(1-\kappa)/(1-\lambda)$.[14] Inserting (8) into (2) gives

$$P_{it} = \mu_t + \frac{1-\phi}{\phi\theta} Q_{jt} - \frac{\alpha}{\phi}\left(I_{it} - I^*_i\right) + \frac{\gamma}{\phi} D_t. \tag{9}$$

To test this equation, we need to replace μ_t which is unobservable to the econometrician. The usual way to do this (e.g. Madhavan and Smidt, 1991; Lyons, 1995) is to express the period t prior belief as equal to the period $t-1$ posterior, plus an expectational error term ε_{it}. The error term represents public information that arrives between trades. Hence,

$$\mu_t = \mu_{it-1} + \varepsilon_{it} = P_{it-1} + \alpha\left(I_{it-1} - I^*_i\right) - \gamma D_{t-1} + \varepsilon_{it}. \tag{10}$$

Substituting this expression for μ_t into (9), gives

$$\Delta P_{it} = \left(\frac{\alpha}{\phi} - \alpha\right) I^*_i + \left(\frac{1-\phi}{\phi\theta}\right) Q_{jt} - \left(\frac{\alpha}{\phi}\right) I_{it} + \alpha I_{it-1} + \left(\frac{\gamma}{\phi}\right) D_t - \gamma D_{t-1} + \varepsilon_{it}. \tag{11}$$

Thus, the baseline model to test is

$$\Delta P_{it} = \beta_0 + \beta_1 Q_{jt} + \beta_2 I_{it} + \beta_3 I_{it-1} + \beta_4 D_t + \beta_5 D_{t-1} + \varepsilon_{it}, \tag{12}$$

where

$$\varepsilon_{it} = \beta_6 \nu_{it-1} + \nu_t, \nu_t \sim IID\left(0, \sigma^2_\nu\right). \tag{13}$$

This baseline model corresponds to the model in Lyons (1995), excluding his variable on market wide order flows. Since we are computing the price change between to successive incoming trades, the perfect collinearity between inventory and trade quantity breaks down. The error term in (13) is MA(1) with $\beta_6 < 0$ due to the use of former incoming trade as an proxy for this periods prior belief (See Appendix). The coefficients β_1 and β_3 measure the information effect and inventory effect, respectively, while β_4 measure

[14] In the model it is assumed that the precision of a signal reflected in θ is the same for all dealers. However, larger banks see more customer order flow. Thus, the assumption of equal precision may not hold. Since dealers know the identity of the counterparty in a bilateral trade, one can argue that they also have some knowledge of their precision. In broker trades the counterparty is anonymous when quoting. With information on counterparties, it is possible to construct variables that captures this by interviewing the dealers in question about whether a specific bank are better or worse informed than him (see Bjønnes and Rime, 2000).

the transaction costs for small quantities. The model predicts that $\{\beta_1, \beta_3, \beta_4\} > 0$, $\{\beta_2, \beta_5\} < 0$, $|\beta_2| > \beta_3$, $\beta_4 > |\beta_5|$. The latter inequalities derive from the fact that $0 < \phi < 1$.

4 Results

In this section we start with presenting some descriptive statistics on the regression variables (section 4.1). Estimation results for the baseline model are presented in section 4.2. Here, our results are directly comparable to similar studies, for instance Lyons (1995) and Madhavan and Smidt (1991). Next, we discuss possible information and inventory effects in section 4.3.

4.1 Descriptive statistics

The baseline model focus on the pricing decision in incoming transactions. Among the interbank transactions, we can determine whether a deal is incoming or outgoing for all of the electronic trades, i.e. direct trades on D2000-1 and indirect trades on D2000-2 and EBS. For our dealers, between 94 and 100% of all trades are signed. Voice-broker trades and telephone trades are excluded from the analysis because they are not signed. These trades are also less important to our dealers. 65% of the signed interbank trades are incoming. Dealer 2 has the lowest share of incoming trades (43%), while Dealer 3 has the highest share (76%).

Tables 7 and 8 report sample moments and a sample correlation matrix for incoming trades for relevant variables used in estimation plus inter-transaction times. The average inter-transaction time varies between five and sixteen minutes, while the median inter-transaction time varies between one minute and eight minutes. The average absolute price changes in DEM/USD are between 4.5 and 6.9 pips, while the medians vary between 2 and 4 pips. For Dealer 3, the average absolute change is 12.1 pips, and the median is 10 pips. Standard deviations varies between 7.7 pips and 11 pips for the DEM/USD dealers, while the standard deviation is 16.8 pips for the NOK/DEM dealer. There are some extreme observations. For instance, for Dealer 1 the lowest price change is more than ten standard deviations away from the mean. Typically, the quoted spread for DEM/USD is of the magnitude 1 to 3 pips, while the quoted spread in NOK/DEM varies between 5 and 30 pips. With an NOK/DEM exchange rate of 4.16, this is 1.2 and 7.2 DEM pips.

Dealer 2, 3 and 4 trade in several currency pairs. However, to have sufficient observations for analysis we restrict the attention to DEM/USD trading for Daler 2 and 4, and NOK/DEM trading for Dealer 3. Dealer 1 only trades in DEM/USD. Hence, for Dealer 1, Dealer 2 and Dealer 4 we focus on the USD inventory, while for Dealer 3 the DEM inventory is the relevant inventory. Since the exchange rate is the relative price between two currencies, the DEM inventories for the three DEM/USD dealers need not mirror the USD inventory exactly. Similarly, the NOK inventory of Dealer 3 may not mirror his DEM inventory exactly. This is a potential problem for Dealer 2, Dealer 3 and Dealer 4 since they trade in several currency pairs. We believe that a DEM/USD dealer located in Europe face higher risks with a USD inventory than a DEM inventory. Similarly, a dealer in NOK/DEM working in Norway will most likely be more concerned about his DEM inventory than his NOK inventory. The correlation between Dealer 2's USD and DEM inventories

Table 7: Descriptive statistics: Sample moments for incoming trades

		ΔP_{it}	Abs(ΔP_{it})	Q_{jt}	Abs(Q_{jt})	I_{it}	Abs(I_{it})	Δt
	Mean	0.1	4.5	0.25	1.80	-0.05	4.25	5.22
Dealer	Median	0.0	3.0	1.00	1.00	0.00	3.82	2.33
1	Maximum	46.0	82.0	10.00	10.00	18.38	21.82	62.57
DEM/	Minimum	-82.0	0.0	-5.00	0.25	-21.82	0.00	0.00
USD	Std. Dev.	7.7	6.3	2.22	1.32	5.72	3.81	8.14
	Mean	-0.3	6.9	0.18	1.48	0.06	0.67	13.46
Dealer	Median	0.0	4.0	1.00	1.00	0.00	0.00	4.88
2	Maximum	51.0	51.0	3.00	3.00	4.00	4.00	69.75
DEM/	Minimum	-50.0	0.0	-3.00	0.50	-3.00	0.00	0.02
USD	Std. Dev.	11.0	8.6	1.64	0.71	1.16	0.95	17.47
	Mean	0.4	12.1	-0.85	3.77	1.17	9.50	15.69
Dealer	Median	0.0	10.0	-0.28	2.00	1.72	6.10	7.64
3	Maximum	50.0	55.0	20.00	40.00	48.13	48.13	102.60
NOK/	Minimum	-55.0	0.0	-40.00	0.02	-40.17	0.15	0.02
DEM	Std. Dev.	16.8	11.7	6.40	5.24	13.25	9.27	20.03
	Mean	-0.1	4.5	-0.20	1.53	-0.50	2.07	7.34
Dealer	Median	-0.1	2.0	-1.00	1.00	-0.76	1.76	0.55
4	Maximum	40.0	41.0	5.00	5.00	8.24	10.76	373.42
DEM/	Minimum	-41.0	0.0	-5.00	1.00	-10.76	0.00	0.00
USD	Std. Dev.	8.0	6.7	1.73	0.83	2.64	1.71	30.71

ΔP_{it} is the change in price between to incoming trades in pips, and Abs(ΔP_{it}) is the absolute value of this change. Q_{jt} is signed incoming trade measured in millions, positive for a purchase from dealer j, and negative for a sale. Abs(Q_{jt}) is the absolute value of each incoming trade. I_{it} is inventory at the end of period t, and Abs(I_{it}) is the absolute value of the inventory. Δt is inter-transaction time between two incoming trades in minutes. Sample: One week in March 1998.

is -0.98, while the correlation between Dealer 4's USD and DEM inventories is -0.53. The correlation between Dealer 3's DEM and NOK inventories is -0.79.

From the sample correlation matrix (table 8), we see that many of the simple correlations are low in absolute value. However, all the regressors have the expected sign. Typically, the correlations between Q_{jt} and ΔP_{it} and between D_t and ΔP_{it} are significantly different from zero, while the correlations between ΔI_{USD} and ΔP_{it} is insignificant. Dealer 3 is the exception. In this case, the simple correlation between ΔI_{USD} and ΔP_{it} is also significant. Inter-transaction time is uncorrelated with model variables except for Dealer 3. In this case there is a positive relationship.

4.2 Baseline model

Table 9 presents the results for the four dealers over the five day sample. The results of Lyons (1995) are also reported for comparison. We have deleted the overnight price changes since it is the pricing decision intra day the model is intended to explain. In most formulations we use the Generalized Method of Moments (GMM) estimation of Hansen (1982), with the Newey and West (1987) correction of the covariance matrix for heteroscedasticity and autocorrelation of unknown form. Madhavan and Smidt (1991) and Yao (1998) use GMM, while Lyons (1995) uses the Hildreth-Lu procedure which is a linear estimation procedure for autoregressive error terms. We choose GMM because (i) it does not require the usual normality assumption, and because (ii) standard errors can be adjusted to take account of both heteroscedasticity and serial correla-

Table 8: Descriptive statistics: Sample correlation matrix, incoming trades

		ΔP_{it}	Q_{jt}	I_{it}	ΔI_{it}	D_t	Δt
	ΔP_{it}	1.00					
	Q_{jt}	0.13	1.00				
Dealer	I_{USD}	-0.01	-0.27	1.00			
1	ΔI_{USD}	-0.06	-0.50	0.30	1.00		
	D_t	0.18	0.80	-0.20	-0.41	1.00	
	Δt	-0.05	-0.02	-0.03	-0.06	0.00	1.00
	ΔP_{it}	1.00					
	Q_{jt}	0.13	1.00				
Dealer	I_{USD}	-0.01	-0.27	1.00			
2	ΔI_{USD}	-0.06	-0.50	0.30	1.00		
	D_t	0.18	0.80	-0.20	-0.41	1.00	
	Δt	-0.05	-0.02	-0.03	-0.06	0.00	1.00
	ΔP_{it}	1.00					
	Q_{jt}	0.27	1.00				
Dealer	I_{DEM}	-0.18	-0.41	1.00			
3	ΔI_{DEM}	-0.16	-0.55	0.35	1.00		
	D_t	0.41	0.58	-0.32	-0.32	1.00	
	Δt	0.17	0.15	-0.14	-0.15	0.11	1.00
	ΔP_{it}	1.00					
	Q_{jt}	0.21	1.00				
Dealer	I_{USD}	-0.05	-0.16	1.00			
4	ΔI_{USD}	-0.08	-0.65	0.37	1.00		
	D_t	0.23	0.88	0.01	-0.55	1.00	
	Δt	0.02	0.08	-0.02	-0.05	0.00	1.00

ΔP_{it} is the change in price between to incoming trades. Q_{jt} is signed incoming trade measured in millions, positive for a purchase from dealer j, and negative for a sale. I_{it} is inventory at the end of period t. D_t is an indicator variable picking up the direction of the trade, positive for purchases (at the ask) and negative for sales (at the bid). Δt is inter-transaction time between two incoming trades.

Table 9: Results for the baseline model, equation (12). Regression of ΔP_{it} between incoming trades

	Dealer 1 DEM/USD	Dealer 2 DEM/USD	Dealer 3 NOK/DEM	Dealer 4 DEM/USD	Lyons DEM/USD
Constant	0.01	-0.86	-1.24	0.92	-0.13
	(0.04)	(-1.05)	(-1.14)	(1.24)	(-0.99)
Trade Q_{jt} (+)	-0.13	-0.96	0.13	-1.41	0.14
	(-0.50)	(-1.11)	(0.50)	(-0.89)	***(3.03)
Inventory I_t (-)	0.06	2.52	-0.07	-0.80	-0.10
	(0.55)	***(3.19)	(-0.37)	(-0.75)	***(-3.56)
Inventory I_{t-1} (+)	-0.03	-0.98	-0.13	0.36	0.08
	(-0.30)	(-0.79)	(-0.67)	(0.37)	***(2.95)
Direction D_t (+)	1.65	5.24	5.38	3.62	1.04
	***(2.47)	***(3.03)	***(3.59)	**(1.96)	***(4.86)
Direction D_{t-1} (-)	-0.25	-1.07	-7.26	-0.23	-0.92
	(-0.71)	(-1.65)	***(-5.31)	(-0.29)	***(-6.28)
AR(1)	-0.06	-0.09	0.03	0.04	-0.01
	(-1.02)	(-0.91)	(0.49)	(1.02)	***(-2.61)
Adjusted R^2	0.02	0.08	0.23	0.01	0.22
Durbin-Watson stat	1.99	1.97	2.10	2.00	
Observations	432	186	144	272	839

Estimated by GMM and variable Newey-West correction. t-values in parenthesis, and "***", "**" and "*" indicate significance at the 1%, 5% and 10%-level respectively. All coefficients multiplied by 10^4, except the AR(1) term. "Lyons DEM/USD" is from Lyons' (1995). He uses the Hildreth-Lu procedure. The dependent variable is ΔP_{it}, and is the change in price between to incoming trades. Q_{jt} is signed incoming trade measured in millions, positive for a purchase from dealer j, and negative for a sale. I_{it} is inventory at the end of period t. D_t is an indicator variable picking up the direction of the trade, positive for purchases (at the ask) and negative for sales (at the bid). The "+" and "-" in parentheses in the first row indicate the expected sign of the coefficient. We use all incoming trades at the D2000-1 (direct trading), D2000-2 and EBS (indirect trading)

tion. In most of the estimations the set of instruments equal the set of regressors. In this case, the parameter estimates parallel OLS parameter estimates. Whether we use GMM or Hildreth-Lu does not affect any of our conclusions.

The model receives very little support when estimated for our dealers. The "+" and "-" in parentheses in the first row indicate the expected sign of the coefficient. The only variables that are correctly signed and significant are the coefficients on D_t and D_{t-1}, which measure the effective spread for Q_{jt} close to zero. For DEM/USD the estimated baseline spread, D_t, varies between 3.3 to 10.5 pips. These estimates are implausible high. For NOK/DEM the estimated spread is 10.8. There is no evidence that dealers increase the quoted spread when volume (Q_{jt}) increases due to private information. Similarly, there is no evidence that dealers adjust their quotes to induce a trade in a certain direction, so to control inventory.

In search for information and inventory effects, we did several experiments. First, we excluded small trades (less than one million). Second, we tried to exclude extreme observations (large price changes). Third, we included customer orders in the sample. Fourth, we addressed the potential importance of transaction time. The Madhavan and Smidt model does not imply any relation between inter-transaction time and the information content of order flow. However, other modelling approaches suggest such a relationship. In Easley and O'Hara (1992) order flow is more informative when trading intensity is high, while Admati and Pfleiderer (1988) suggest the opposite. None of the experiments changed the results presented in table 9 significantly.

Next, consider the results for Lyons dealer. Here, all coefficients have expected signs and are significantly different from zero. From the coefficient on D_t, the estimated baseline spread is 2.1 pips (2×1.04). The dealer widens his spread with 2.8 pips ($2 \times 0.14 \times 10$) per USD ten million to protect against adverse selection. Furthermore, the dealer tends to motivate inventory decumulation by shading the price by 0.8 pips (10×0.078) for every USD ten million of net open position.

4.3 Discussion

The two most obvious explanations for these different results are (*i*) difference in trading styles and (*ii*) changes in trading environment. Of course, as the message of this paper and microstructure theory in general, the two explanations are interrelated. Lyons' dealer is a typical "jobber", that is, he makes money from the bid and ask spread in the interbank market. To earn money he must be at the favorable side of the bid and ask most of the time. This means that the majority of trades must be incoming. Of total 952 signed trades, 843 are incoming. Most of his trading is through the direct system D2000-1.[15] As discussed in section 2.1, direct trading is probably the most informative trading channel. The dealer also had agreements to trade with several large dealers, making it important to protect against private information. This may explain the information effect. The inventory effect may also be explained by his trading style. Given that most of the trades are direct incoming, he must wait for other dealers to initiate a trade. To attract trades, and then earn from the bid and ask spread, he must give competitive quotes. By shading quotes he makes one price particularly attractive. Furthermore, he did not have any customer order flow, i.e. no private information signals, and hence would be less worried about that shading of prices for control of inventory would signal his inventory. However, as a major dealer he took part in a lot of informative trading. Finally, in 1992 when Lyons' dealer operated, trading opportunities were limited to direct trading through D2000-1 or telephone, or indirect trading through voice-brokers. Among these, D2000-1 was the most popular. A majority of direct trading went through D2000-1 (over 90% a couple of years later, according to Evans and Lyons (1999)), and between 60 and 70% of interbank trades were direct in 1992 (BIS, 1993).

Like Lyons' dealer, Dealer 1, Dealer 2 and Dealer 4 have only limited customer order flows. However, these dealers do not make money from the bid and ask spread. For Dealer 1 and Dealer 2 more than 50% of the interbank trading volume were outgoing. For Dealer 4, 41% of the interbank trading volume were outgoing. Thus, it seems that these dealers try to make money from exchange rate movements, and therefore must use outgoing trades, instead of "earning" half of the spread by giving quotes in incoming trades. In doing so, all three dealers rely heavily on electronic broker systems. They take limited positions for a short time. Most pronounced is this trading strategy for Dealer 2. The size of the position taking depends on the liquidity of the electronic broker systems. Execution speed and price are important. Instead of trading large quantities, they frequently trade smaller quantities. Thus, their trading style may explain the insignificant coefficients.

Dealer 3 has large customer order flows. He told us that he refuses to use bid shading because he was concerned about signalling his inventory position to other dealers. The lack of any information effect is

[15] In fact, Lyons' (1995) sample for estimation consists exclusively of transactions executed by D2000-1.

harder to explain. Can his position as the largest Market Maker in this market be of importance? The data in Bjønnes and Rime (2000) indicate that he regards most his counterparts as inferiorly informed.

As we have seen, there are several reasons to believe that the model is better suited for "jobbers" like Lyons' dealer than for other types of dealers. In a survey by Cheung et al. (2000), dealers in UK were asked which best characterized their dealing method. The answers were equally shared between the four categories: "Technical trading-based", "Customer orders-based", "Fundamentals-based" and "Jobbing". Our dealers belong to the three first mentioned categories. Further, between 1992/1993 and 1997/1998, the share of dealers that said they belonged to the "Jobber" category decreased remarkably. Is the introduction of electronic broking systems and tiny spreads some of the explanation for this dramatic fall in this category? In the survey the dealers were also asked about which factors that determine the spread. Most important was the "market convention". If they change the spread from the "market norm", liquidity was the most important factor. Changing volume and inventory effects were considered as less important. These answers may explain some of our failures to find evidence of any information or inventory effect.[16]

Multicollinearity may possibly explain the missing information and inventory effect. As seen in table 8, there is a problem with high correlation between the D_t variable and both Q_{jt} and I_{it}.

We will proceed with investigating information and inventory effects under the new microstructure. First we study spreads from direct trading more closely. In the next section we extend the baseline model to see if there are differences in informational content or behavior parameters between direct or indirect trading. Next, we address one of the possible microstructural consequences of the introduction of electronic brokers, namely that dealers observe more of the aggregate order flow. We end by looking at inventory control from other angles than the one captured in the baseline model. It has been infeasible for us to develop stringent models for all investigations that follow.

4.3.1 Information effect

Spread To examine this more closely, we consider all direct trades (D2000-1) by Dealer 1 and Dealer 3 where two-way quotes are available. Bid and ask quotes are available for 62 of Dealer 2's trades and for 61 of Dealer 3's trades. All trades were executed at the bid or the ask.

First, consider Dealer 1 (see table 10). The average spread is 1.8 pips for quantities less than USD one million, increasing to 2.1 pips for quantities between 1 and 5 million. For quantities between USD 5 and 10 million the average spread is 2.3 pips, while for trades above USD 10 billion we have one observation of 3 pips. However, note that there are only four observations for quantities above USD five million. The maximum spread is four pips, while the minimum spread is one pip. The simple correlation between absolute size and spread is 0.46. Thus, there is some evidence that Dealer 1 quote larger spreads when trading larger quantities.

Next, consider Dealer 3. Table 11 shows a clear relationship between absolute size and spread. For

[16] However, "market conventions" may include an private information component (see Table 12 in the next section). Typically, large dealers establish such "market conventions", for instance that their quotes are good for at least USD 10 million and that the spread is fixed. For larger amounts (for instance USD 50 million) there can be another "market convention" with a wider spread. Thus, even with "market conventions" the spread may widen with quantity traded. This is not recognized by Cheung et al. (2000).

Table 10: Observed spread from D2000-1 trades for Dealer 1

	Absolute quantity				
	<1	1-5	5-10	10-	All
Average	1.8	2.1	2.3	3.0	2.0
Median	2	2	2	3	2
Max	3	4	3	3	4
Min	1	1	2	3	1
Std.	0.5	0.5	0.6	NA	0.5
Correlation					0.46
Obs.	23	35	3	1	62

The spread (pips) is observed from the D2000-1 conversations which resulted in a trade. In 16 of the D2000-1 trades the counterparty asked only for a one-way price (or the conversation could be missing), that is, the spread could not be observed. Spread is measured in pips. Correlation is the simple correlation between the spread and absolute transaction size.

amounts less than DEM 5 million, the average spread is close to 10 pips. For amounts between DEM 5 and 10 million the average spread increases to 15 pips, while the average spread for DEM 10 million or more is close to 30 pips. The spread varies between 5 and 30 pips. The correlation between absolute size and spread is high, 0.84. The spread for all trades of DEM 10 million are 30 pips. This is the "market norm" among the market makers. Interestingly, there are a couple of transactions for more than DEM 10 million. For both these trades the spread is lower than 30 pips.

Table 11: Observed spread from D2000-1 trades for Dealer 3

	Absolute quantity				
	<1	1-5	5-10	10-	All
Average	11.2	8.6	15.0	28.4	15.5
Median	10	10	15	30	10
Max	15	15	15	30	30
Min	5	5	15	15	5
Std.	3.0	3.8	NA	4.4	8.5
Correlation					0.84
Obs.	37	7	1	16	61

See table 10.

To formally test whether the quoted spread increases with quantity, we pool all the direct trades. We run the following regression,

$$Spread = \beta_0 + \beta_1 \cdot abs(Q_{jt}) + \varepsilon_{it}, \tag{14}$$

where abs(Q_{jt}) is the absolute quantity. The results are shown in table 12. The estimated spread for a USD one million trade (DEM/USD) is 1.90 pips, while the estimated spread for a DEM one million trade is 13.5 pips (NOK/DEM). The coefficient on absolute quantity traded is positive and significantly different from zero for both DEM/USD and NOK/DEM. In DEM/USD the quoted spread widens with 1.40 pips per USD ten million traded, and with 15.0 pips per DEM ten million traded for NOK/DEM. The estimated spread for a USD ten million trade is 3.2 pips ($1.76 + 1.4$). Note that this increase in quoted spread is much smaller than estimated by Lyons for the effective spread to protect against adverse selection. Lyons estimated the effective spread to 4.8 pips for USD ten million on observations from 1992. In NOK/DEM the estimated quoted spread for a DEM ten million trade is 26 pips which is close to the "market norm" (30 pips). In fact,

Table 12: Results for equation (14). Regression of observed spread from D2000-1 trades on quantity traded

	DEM/USD	NOK/DEM
Constant	1.76	10.98
	***(22.54)	***(12.52)
Abs(Q_{jt})	0.14	1.50
	***(4.12)	***(9.51)
Adjusted R^2	0.21	0.60
Durbin-Watson stat	0.92	2.61
Observations	67	62

Estimated by OLS. t-values in parenthesis, and "***", "**" and "*" indicate significance at the 1%, 5% and 10%-level respectively. All coefficients multiplied by 10^4. The dependent variable is the observed spread in pips. $Abs(Q_{jt})$ is the trade (absolute) quantity measured in millions.

the quoted spreads for all DEM 10 million trades are all 30 pips.

In trades executed by electronic brokers, we are not able to observe the spread. Next, we want to test whether the effective spread increases with quantity in the electronic broker market. As shown in table 9 one may argue that bid shading is not very likely for controlling inventory in foreign exchange markets. Thus, we set $\alpha = 0$. The resulting model is now

$$\Delta P_{it} = \left(\frac{1-\phi}{\phi\theta}\right) Q_{jt} + \left(\frac{\gamma}{\phi}\right) D_t - \gamma D_{t-1} + \varepsilon_{it}. \tag{15}$$

This model is very close to the Glosten and Harris (1988) model. The only exception is that in their model the coefficients on D_t and D_{t-1} are restricted to be identical.[17]

We use the following regression equation to estimate possible information effects and effective bid and ask spread in the electronic broker market:

$$\Delta P_{it} = \beta_1 Q_{jt} + \beta_4 D_t + \beta_5 D_{t-1} + \varepsilon_{it}. \tag{16}$$

To increase estimation power, we pool all the incoming trades for the different dealers. The estimated baseline bid and ask spread for DEM/USD is 2.8 pips, and 16.6 pips for NOK/DEM. We find no evidence of any information effect (table 13). However, we should be careful with interpreting these results such that spread does not increase with quantity. Probably, the dealers examine the bid and ask and how much can be traded at the bid and ask before they decide how much to trade. Therefore, they trade for larger quantities when the market is deep.

Direct vs. indirect trading The information effect and the degree of bid shading may depend on the trading system used. As mentioned in Section 2, there are at least four important differences between direct and indirect trading. These four characteristics suggest that broker trades may be less informative than trades executed directly. It is also likely that dealers shade quotes differently depending on whether they trade direct or indirect. In direct trades dealers may be afraid of using bid shading since this might signal

[17] If we assume that there is neither any information effect ($\phi = 1$) nor any inventory effect ($\alpha = 0$), the Madhavan and Smith model becomes $\Delta P_{it} = \gamma D_t - \gamma D_{t-1} + \varepsilon_{it}$, wich is the Roll (1984) model, with the assumption that D_t and ε_{it} are independently distributed with zero means.

Table 13: Results for equation (16). Regression of ΔP_{it} between incoming, electronic brokered, trades.

	DEM/USD	NOK/DEM
Trade Q_{jt}	0.105	-0.413
	(0.60)	(-1.02)
Direction D_t	1.400	8.302
	***(3.68)	***(5.56)
Direction lagged D_{t-1}	-0.336	-2.294
	*(-1.95)	**(-2.08)
AR(1)	-0.045	-0.045
	(-0.98)	(-0.58)
Adjusted R^2	0.07	0.18
Durbin-Watson stat	2.00	1.91
Observations	891	145

Estimated by GMM and variable Newey-West correction. t-values in parenthesis, and "***", "**" and "*" indicate significance at the 1%, 5% and 10%-level respectively. All coefficients multiplied by 10^4, except the AR(1) term. The dependent variable is ΔP_{it} is the change in price between to incoming (electronic brokered) trades. Q_{jt} is signed incoming trade measured in millions, positive for a purchase from dealer j, and negative for a sale. D_t is an indicator variable picking up the direction of the trade, positive for purchases (at the ask) and negative for sales (at the bid). We pool data for all dealers.

their position. This is not the case in indirect trades. Therefore, we expect dealers to shade quotes less when trading direct.

We model the information content in the different trading systems such that the updated belief depends on which system is used, hence,

$$\mu_{it} = d_t \left[\kappa^{\mathrm{D}}\mu_t + \left(1-\kappa^{\mathrm{D}}\right) Z_{jt}\right] + (1-d_t)\left[\kappa^{\mathrm{I}}\mu_t + \left(1-\kappa^{\mathrm{I}}\right) Z_{jt}\right], \tag{17}$$

where d_t is a dummy that equals one if the trade is direct and zero if the trade is indirect, and Z_{jt} is defined as in equation (6). The superscript "D" means direct, while the superscript "I" means indirect, so κ^{D} and κ^{I} are the weights on prior belief when the trade is direct and indirect, respectively. The hypothesis is that Z_{jt} is a more precise signal in direct trades, that is, $\kappa^{\mathrm{D}} < \kappa^{\mathrm{I}}$. This implies that $\phi^{\mathrm{D}} < \phi^{\mathrm{I}}$ in the updating formula (see appendix).

We also open for the possibility that dealers' inventory control behavior differ on different systems, such that

$$P_{it} = \mu_{it} - \left[\alpha^{\mathrm{D}} d_t + \alpha^{\mathrm{I}}(1-d_t)\right](I_{it} - I_i^*) + \gamma D_t. \tag{18}$$

The relative size of α^{D} and α^{I} is not obvious. It may be that the risk of revealing your inventory through shading in direct trading makes $\alpha^{\mathrm{D}} < \alpha^{\mathrm{I}}$. However it may also be that the high degree of liquidity on the electronic brokers makes shading unnecessary, so $\alpha^{\mathrm{I}} = 0$.

Given that there already exist different trading systems with very different characteristics in the market, and has done so for several years, we believe such an description of information content and dealer behavior as above may be part of a equilibrium. We do not pretend however that this is derived from first principles.

Inserting (17) into (18), and replacing for μ_t in a similar manner as before, gives

$$\begin{aligned}\Delta P_{it} = &\left[\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}} d_t + \frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}}(1-d_t)\right] I_i^* - \left[\alpha^{\mathrm{D}} d_{t-1} + \alpha^{\mathrm{I}}(1-d_{t-1})\right] I_i^* \\ &+ \left[\frac{1-\phi^{\mathrm{D}}}{\phi^{\mathrm{D}}\theta} d_t + \frac{1-\phi^{\mathrm{I}}}{\phi^{\mathrm{I}}\theta}(1-d_t)\right] Q_{jt} - \left[\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}} d_t + \frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}}(1-d_t)\right] I_{it} \\ &+ \left[\alpha^{\mathrm{D}} d_{t-1} + \alpha^{\mathrm{I}}(1-d_{t-1})\right] I_{it-1} + \left[\frac{\gamma}{\phi^{\mathrm{D}}} d_t + \frac{\gamma}{\phi^{\mathrm{I}}}(1-d_t)\right] D_t - \gamma D_{t-1} + \varepsilon_{it} \qquad (19)\end{aligned}$$

Therefore, the model to test is

$$\begin{aligned}\Delta P_{it} = &\beta_0 + \beta_0' d_t + \beta_0'' d_{t-1} + \beta_1^{\mathrm{D}} d_t Q_{jt} + \beta_1^{\mathrm{I}}(1-d_t) Q_{jt} + \beta_2^{\mathrm{D}} d_t I_{it} + \beta_2^{\mathrm{I}}(1-d_t) I_{it} \\ &+ \beta_3^{\mathrm{D}} d_{t-1} I_{it-1} + \beta_3^{\mathrm{I}}(1-d_{t-1}) I_{it-1} + \beta_4^{\mathrm{D}} d_t D_t + \beta_4^{\mathrm{I}}(1-d_t) D_t + \beta_5 D_{t-1} + \varepsilon_{it}. \qquad (20)\end{aligned}$$

The model predicts that $\{\beta_1^{\mathrm{D}}, \beta_1^{\mathrm{I}}, \beta_3^{\mathrm{D}}, \beta_3^{\mathrm{I}}, \beta_4^{\mathrm{D}}, \beta_4^{\mathrm{I}}\} > 0, \{\beta_2^{\mathrm{I}}, \beta_2^{\mathrm{D}}, \beta_5\} < 0$. The coefficient β_5 is the same as in the benchmark model. The coefficients β_1^{D} and β_1^{I} capture the information effect, while β_3^{D} and β_3^{I} capture the inventory control effect. If the information effect is more important when trading direct, we expect that β_1^{D} is significantly greater than β_1^{I}. We also expect that quote shading is less attractive in direct trades. If this is the case, β_3^{I} should be significantly greater than β_3^{D}. The error term will be MA(1) of the same reasons as above.

In table 14 we test this model. This test is only conducted for Dealer 1 and 3 since they are the only dealers with sufficient transactions at the direct trading system D2000-1. Again the baseline spread variables enter with correct sign. This formulation however shows that at least for DEM/USD (Dealer 1) the direct trading channel seems to be more informative with an significant information effect coefficient on Q_{jt}. Dealer 1 increases his spread with 2 pips for a USD 1 million trade. This number is implausible large. However, the coefficient is only significantly different from zero at the ten percent level. Somewhat surprising is that for Dealer 1 the indirect baseline spread $(1-d_t)D_t$ is larger than the direct baseline spread $d_t D_t$. The opposite is the case for Dealer 3, where also there is a positive and significant effect from indirect trades.

Table 15 presents estimation results for direct trades alone. This table confirms the information effect for DEM/USD, There are also indications that the Madhavan-Smidt model probably is better suited for direct trading than indirect trading, as indicated by the increased fit in the regression for Dealer 1.

Cumulative flow One of the potentially most important consequences of the introduction of the electronic brokers is that the market may become more transparent as more trading is done through this channel. This is because the dealers can observe the direction of all trades conducted on the electronic brokers, and hence see more of the market flow.

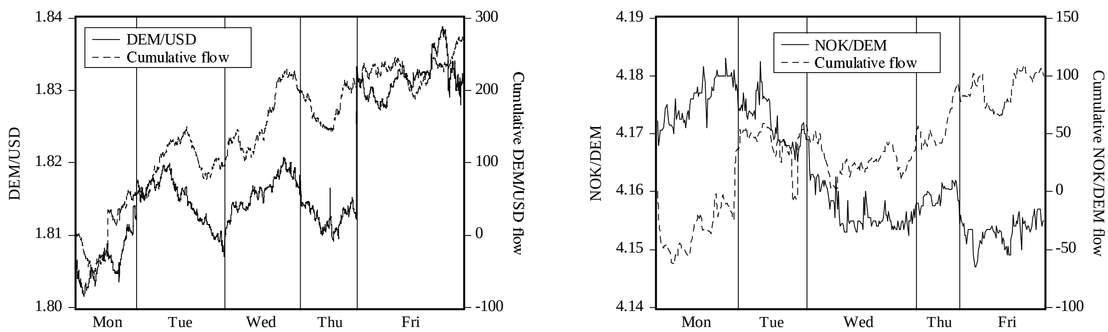
As a larger part of the flow become observable, dealers might give more attention to the flow on the brokers than on single trades. In figure 6 we draw the exchange rate and the cumulative order flow on the electronic brokers. The cumulative flow is created by using the direction and size of the initiator in any trade the bank's FX department is part of on the electronic brokers. Although the cumulative flow only

Table 14: Results for the system model, equation (20). Regression of ΔP_{it}

	Dealer 1 DEM/USD	Dealer 3 NOK/DEM
Constant	-0.25	-1.20
	(-0.59)	(-0.55)
Direct dummy d_t	-0.02	0.71
	(-0.02)	(0.21)
Direct dummy d_{t-1}	0.99	3.10
	(1.05)	(1.19)
Direct trade $d_t Q_{jt}$ (+)	1.07	-0.07
	*(1.86)	(-0.20)
Indirect trade $(1-d_t)Q_{jt}$ (+)	-0.37	1.10
	(-1.16)	**(2.11)
Inventory $d_t I_{it}$ (-)	0.37	-0.22
	(1.48)	(-1.02)
Inventory $(1-d_t)I_{it}$ (-)	0.09	0.10
	(0.72)	(0.56)
Inventory $d_{t-1}I_{it-1}$ (+)	0.03	0.09
	(0.14)	(0.52)
Inventory $(1-d_{t-1})I_{it-1}$ (+)	-0.11	-0.17
	(-1.07)	(-0.72)
Direct $d_t D_t$ (+)	1.42	6.55
	(1.42)	***(5.14)
Indirect $(1-d_t)D_t$ (+)	1.91	2.30
	**(2.39)	(0.71)
D_{t-1} (-)	-0.37	-2.46
	(-1.02)	(-1.53)
MA(1)	-0.04	-0.16
	(-0.63)	***(-2.79)
Adjusted R^2	0.04	0.20
Durbin-Watson stat	1.97	2.03
Observations	432	143

Estimated by GMM and variable Newey-West correction. t-values in parenthesis, and "***", "**" and "*" indicate significance at the 1%, 5% and 10%-level respectively. All coefficients multiplied by 10^4, except the AR(1) term. The dependent variable is ΔP_{it} is the change in price between to incoming trades. Q_{jt} is signed incoming trade measured in millions, positive for a purchase from dealer j, and negative for a sale. I_{it} is inventory at the end of period t. D_t is an indicator variable picking up the direction of the trade, positive for purchases (at the ask) and negative for sales (at the bid). d_t is a dummy variable taking the value 1 if the trade is direct and 0 otherwise. The "+" and "-" in parentheses in the first row indicate the expected sign of the coefficient.

Figure 6: Transaction prices and Cumulative order flow



Transaction prices and cumulative trading in DEM/USD (left), and NOK/DEM (right) during the week. The source is all the spot transactions conducted electronically by the whole FX department of the bank. The horizontal axis is in "transaction"-time. Vertical lines indicate end of day.

Table 15: Results for baseline model, equation (12). Regression of ΔP_{it} in incoming direct trades.

	Dealer 1 DEM/USD	Dealer 3 NOK/DEM
Constant	0.42	-2.24
	(0.40)	(-1.23)
Trade Q_{jt} (+)	1.66	-0.73
	**(2.07)	(-1.42)
Inventory I_{it} (-)	1.02	-0.80
	*(1.71)	(-1.46)
Inventory I_{itt-1} (+)	-0.81	0.41
	(-1.62)	(0.69)
Direction D_t (+)	1.79	4.90
	(1.58)	***(3.12)
Direction D_{t-1} (-)	-1.42	-7.29
	(-1.38)	***(-3.64)
Adjusted R^2	0.10	0.20
Durbin-Watson stat	1.84	1.93
Observations	75	87

Estimated by GMM and variable Newey-West correction. t-values in parenthesis, and "***", "**" and "*" indicate significance at the 1%, 5% and 10%-level respectively. All coefficients multiplied by 10^4, except the AR(1) term. The dependent variable is ΔP_{it}, and is the change in price between to incoming trades. Q_{jt} is signed incoming trade measured in millions, positive for a purchase from dealer j, and negative for a sale. I_{it} is inventory at the end of period t. D_t is an indicator variable picking up the direction of the trade, positive for purchases (at the ask) and negative for sales (at the bid). The "+" and "-" in parentheses in the first row indicate the expected sign of the coefficient. We use only incoming trades through the D2000-1 (direct trading).

incorporates the trading of this specific bank, we believe it is sufficiently representative of the trading of the market since it is based on the trading of a total of 19 dealers, and since it is not limited to the initiatives of this specific bank only. In particular for the DEM/USD rate, there seems to be a strong relation between the two variables. Figure 6 is very similar to the figures in Evans and Lyons (1999), where they develop a model where the price depends on cumulated signed flow.[18] All the four series in the figure have unit roots. The graphs then suggest that the price and the cumulative flow are cointegrated.

$$\text{DEM/USD: } P_t = 1.80 + \underset{(3.60)}{0.000113}\text{CumFlow}_{DEM/USD} \tag{21}$$

$$\text{NOK/DEM: } P_t = 4.17 - \underset{(-2.72)}{0.000286}\text{CumFlow}_{NOK/DEM} \tag{22}$$

The cointegrating relation for the DEM/USD is significant and correctly signed. A buying pressure of USD, i.e. a large positive cumulative flow, goes together with a high DEM-price of USD. The sign is wrong in the case of NOK/DEM. However, the graph suggest that the relationship is actually positive for several of the

[18]Evans and Lyons (1999) find that price changes depend significantly on unexpected period flow, for daily data. This is further confirmed in Rime (2000a) and Rime (2000b), for weekly data from Norway and U.S.A respectively.

days. When we re-estimate the the cointegrating relationships for each day seperately, we get

$$\text{Monday: } P_t = 4.18 + \underset{(4.89)}{0.000149}\text{CumFlow}_{NOK/DEM} \tag{23}$$

$$\text{Tuesday: } P_t = 4.16 + \underset{(3.41)}{0.000354}\text{CumFlow}_{NOK/DEM} \tag{24}$$

$$\text{Wednesday: } P_t = 4.16 + \underset{(0.64)}{0.000043}\text{CumFlow}_{NOK/DEM} \tag{25}$$

$$\text{Thursday: } P_t = 4.16 - \underset{(-0.35)}{0.000022}\text{CumFlow}_{NOK/DEM} \tag{26}$$

$$\text{Friday: } P_t = 4.18 + \underset{(1.60)}{0.000075}\text{CumFlow}_{NOK/DEM} \tag{27}$$

We find that in four of the five days the cointegrating relationship implies a positive relation. For two of these days it is also significant. Since cointegration is supposed to be a long run relation, it is difficult to interpret these equations. Our main point, however, is to show that the negative relation for the whole week need not imply that this is the case for NOK/DEM in general.

Given that the cumulative flow on the electronic brokers tracks prices, and this is observable for the dealers, the lack of information effect in single trades may be because dealers rather focus on the flow from the electronic brokers to learn currency value.

4.3.2 Inventory control

Figure 2 show that inventory control is important to our dealers. To provide a brief estimate of mean reversion in dealer inventories, we estimate the following regression

$$I_{it} - I_{it-1} = \alpha - \beta I_{it-1} + e_t, \tag{28}$$

where I_{it-1} is the inventory in after the previous trade, incoming or outgoing. Here, the target inventory is assumed to be constant. Most likely, the target inventory changes over time as a result of speculative positions taken (Lyons, 1997).[19] Table 16 presents the results. All constant terms are close to zero, which means that the target inventory is close to zero. This is not a surprise given that most dealers close their positions at the end of the day. All slope coefficients are highly significant, varying between -0.11 and -0.80. The highest estimate means that 80% of deviations from target inventory is reversed during the next trade. With an average intertransaction time of only a few minutes, mean reversion is very fast.

Given that inventory control seem to be at work, there might be effects in incoming trades that we have not uncovered. In particular, in the estimation of the baseline model in table 9 we assumed that the preferred inventory I_{it}^* was a constant. It might very well be time-varying, and Lyons suggested that it may be related to the expectation and hence related to trade Q_{jt}. This still makes a significant coefficient for Q_{jt} representing an information effect, but one should be careful with interpretation of the magnitude.

Another approach to the time varying preferred inventory, which focuses more on estimation of inventory

[19]If we let the target inventory vary, this would probably lead to intensified mean reversion.

Table 16: Results for equation (28). Mean reversion in dealer inventory I_{it}

	Dealer 1 DEM/USD	Dealer 2 DEM/USD	Dealer 3 NOK/DEM	Dealer 4 DEM/USD
Constant	0.04	0.13	0.14	-0.13
	(0.45)	**(2.00)	(0.27)	(-1.41)
Lagged inventory (I_{it-1})	-0.11	-0.80	-0.19	-0.24
	***(-7.30)	***(-17.28)	***(5.11)	***(7.52)
Adjusted R^2	0.05	0.40	0.09	0.12
Durbin-Watson stat	2.30	2.01	2.04	2.18
Observations	912	446	246	421

Estimated by ordinary least squares. t-values in parenthesis, and "***", "**" and "*" indicate significance at the 1%, 5% and 10%-level respectively. The dependent variable is the change in dealer inventories measured in USD or DEM millions from the previous trade (in DEM/USD for Dealer 1, Dealer 2 and Dealer 4 and in NOK/DEM for Dealer 3), incoming or outgoing. I_{it-1} is inventory after the previous trade, incoming or outgoing.

control than information effect, might be to use of the sign of the last outgoing trade's effect on inventory, as suggested by Yao. Information considerations aside, an outgoing purchase when inventory already is positive is an indication that preferred inventory is larger than the present. We implement this with an dummy being $1\,(-1)$ if the preferred inventory was larger (smaller) than the present inventory, according to the test above. This is tested in the baseline model in table 17. All the Signed inventory dummies' coefficients are correctly signed, and significant for dealer 2 and 3.[20]

Table 17: Regression of ΔP_{it} from incoming trades. $(I_{it} - I^*_{it})$ implemented as a dummy, $\{1, -1\}$, from inventory-accumulation in last outgoing trade.

	Dealer 1 DEM/USD	Dealer 2 DEM/USD	Dealer 3 NOK/DEM	Dealer 4 DEM/USD
Constant	-0.04	-0.50	0.57	0.20
	(-0.13)	(-0.63)	(0.48)	(0.38)
Trade Q_{jt} (+)	-0.16	-1.94	0.12	0.20
	(-0.71)	**(-2.00)	(0.46)	(0.39)
Signed Inventory (-)	-0.21	-1.94	-2.87	-0.56
	(-0.48)	***(-2.72)	**(-2.25)	(-1.02)
Inventory I_{t-1} (+)	0.01	-0.10	-0.16	-0.31
	(0.30)	(-0.09)	*(-1.70)	(-1.44)
Direction D_t (+)	1.66	4.25	6.95	1.77
	***(2.63)	***(2.62)	***(5.27)	(1.58)
Direction D_{t-1} (-)	-0.39	-1.25	-2.60	-0.36
	(-1.12)	*(-1.66)	*(-1.71)	(-0.66)
Adjusted R^2	0.03	0.05	0.19	0.05
Durbin-Watson stat	2.10	2.08	2.29	1.82
Observations	432	186	144	273

Estimated by GMM and variable Newey-West correction. t-values in parenthesis, and "***", "**" and "*" indicate significance at the 1%, 5% and 10%-level respectively. All coefficients multiplied by 10^4. The dependent variable is ΔP_{it} is the change in price between to incoming trades. Q_{jt} is signed incoming trade measured in millions, positive for a purchase from dealer j, and negative for a sale. "Signed inventory" is a dummy that represents $(I_{it} - I^*_{it})$, and equals 1 if previous outgoing trade accumulated inventory and -1 otherwise. I_{it-1} is inventory at the end of period $t-1$. D_t is an indicator variable picking up the direction of the trade, positive for purchases (at the ask) and negative for sales (at the bid). The "+" and "-" in parentheses in the first row indicate the expected sign of the coefficient.

[20] One could estimate I^*_{it} as an time varying coefficient with the Kalman filter, for example following a AR(1) process. This approach does not give any additional insights in our case.

Dealers also have several other options for controlling their inventory positions besides shading quotes in incoming trades, as presented in table 18 (except internal trades). Trades that increase the absolute size of the inventory are accumulating, while trades that decrease the absolute size of the inventory are decumulating. The majority of the incoming direct trades are accumulating. This is not surprising. If the dealer previous to an incoming direct trade has an inventory position close to zero, the trade will most likely generate an increase in the absolute inventory position since it is the contacting dealer who decides the quantity.

Table 18: Accumulating and decumulating trades

	Incoming			Outgoing			
		Electronic broker trades		Electronic broker trades			
	Direct D2000-1	D2000-2	EBS	D2000-2	EBS	Voice-broker	Sum
Dealer 1:							
Decumulating	30	39	154	113	98	36	470
Accumulating	48	70	96	163	79	21	477
Dealer 2:							
Decumulating	1	7	131	44	52	NA	235
Accumulating	4	28	20	147	12	NA	211
Dealer 3:							
Decumulating	40	24	0	20	2	9	95
Accumulating	50	35	0	20	2	7	114
Dealer 4:							
Decumulating	NA	66	122	35	15	NA	238
Accumulating	NA	44	46	73	20	NA	183

Trades that increase the absolute size of the inventory are accumulating, while trades that decrease the absolute size of the inventory are decumulating. All direct trades are incoming. Voice-broker trades are not signed.

For three of the dealers, the majority of incoming brokered trades are decumulating. There is no clear tendency that outgoing trades are decumulating. Interestingly, for three of the dealers (Dealer 1, Dealer 2 and Dealer 3) a trading pattern emerges. Most pronounced is this pattern for Dealer 2. Typically, a position is established by an outgoing trade on D2000-2 (accumulating). Next, the position is closed by an incoming trade on EBS (decumulating). The idea behind the trading strategy is to establish a position on the “slow/rigid” system (D2000-2) and closing the position at the “fast system” (EBS), according to the dealers. Thus, they trade outgoing at the “slow system” to initiate a trade. The position is closed by trading incoming at the “fast system”.

Outgoing trades In the foreign exchange market dealers can control their inventory position by trading at other dealers quotes. Trading at other dealers quotes may have turned to be a more attractive option after the introduction of the electronic brokers. When trading outgoing through the D2000-1 a dealer not only have to pay half the spread, but in addition reveals his identity. Outgoing trades on the electronic brokers only leads to the dealer paying half the spread. In both cases the advantage with outgoing trading is that he can time the trade himself if there is quotes available. The dealers in our sample do all their outgoing trade on the electronic brokers.

In table 19 we study closer what motivates incoming and outgoing trade decision. We let the dependent variable be a dummy, which equals 1 if the trade is outgoing and 0 if it is incoming, and estimates propen-

Table 19: Probit-regression of incoming/outgoing trade

	Dealer 1	Dealer 2	Dealer 3	Dealer 4
Constant	-0.367	-0.024	-0.735	-1.178
	***(-3.97)	(-0.16)	***(-4.10)	***(-7.74)
Trade size Abs(Qjt)	0.103	0.030	0.005	0.282
	***(3.95)	(0.34)	(0.29)	***(3.95)
Inventory size Abs(I_{it})	0.033	0.245	0.003	0.060
	***(3.04)	***(3.45)	(0.31)	(1.60)
Price change, Abs(ΔP_{it})	30.379	211.521	-68.113	382.549
	(0.53)	*(1.74)	(-0.96)	***(4.11)
Incoming/Outgoing last trade	-0.034	-0.254	-0.507	-0.071
	(-0.41)	**(-2.02)	*(-1.90)	(-0.52)
McFadden's R^2	0.02	0.06	0.02	0.09
Observations	912	446	246	421

Probit regression of Incoming/Outgoing trade decision. Incoming trades are 0, while outgoing trades are coded 1. R^2 is McFadden's analog to ordinary R^2-measures.

sities to trade incoming or outgoing with a probit regression. There is a tendency that the dealers choose to initiate trades (outgoing) if the last trade was incoming, consistent with the above mentioned trading strategy. For dealer 1 and 2 there are also sign that they use outgoing trades for inventory control, since a large inventory in absolute terms leads to outgoing trades. Absolute price changes are intended to capture volatility, and in case of dealer 2 and 4 this seems to make them rely on outgoing trades.

To test outgoing trades directly, we now let each period be one outgoing trade. Notice that there are no simultaneity between Q_{it} and P_{jt} in an outgoing trade, since all outgoing trades are at the electronic brokers where the individual dealer is price taker. We base the imperical analysis on a version of the demand equation (1) in section 3,

$$Q_{it} = \theta(\mu_{it} - P_{jt}) - \zeta(I_{it} - I_i^*) \tag{29}$$

where $\zeta(I_{it} - I_i^*)$ captures inventory control. For the conditional expectation μ_{it}, we insert

$$\mu_{it} = P_{it-\tau} - \gamma D_{t-\tau} + \tilde{\varepsilon}_{it}. \tag{30}$$

In other words, the conditional expectation is the previous price, $P_{it-\tau}$, irrespective of whether it was incoming or outgoing, corrected for whether it was at the bid or the ask, $\gamma D_{t-\tau}$, and added an expecetational error $\tilde{\varepsilon}_{it}$. When we insert this for μ_{it} into (29) we get

$$Q_{it} = \theta(P_{it-\tau} - \gamma D_{t-\tau} - P_{jt}) - \zeta(I_{it} - I_i^*) + \varepsilon_{it}. \tag{31}$$

The estimable equation becomes

$$Q_{it} = \beta_0 + \beta_1 P_{it-\tau} + \beta_2 D_{t-\tau} + \beta_3 P_{jt} + \beta_4 I_{it-\tau} + \varepsilon_{it}, \tag{32}$$

where we have instrumented for I_{it} with the inventory from previous trade, $I_{it-\tau}$.

The results are presented in table 20, with expected signs in parenthesis. The estimated coefficients on the price variables are either insignificant and/or of wrong sign. The negative coefficient on the inventory variable $I_{it-\tau}$ indicate that if the dealer had a long position in previous incoming trade he would on average place an sell order to decrease his inventory when trading outgoing.

Table 20: Results for equation (32). Regression of outgoing trades

	Dealer 1 DEM/USD	Dealer 2 DEM/USD	Dealer 3 NOK/DEM	Dealer 4 DEM/USD
Constant	-33.111	-6.333	519.879	-92.861
	(-1.15)	(-0.31)	(0.58)	**(-2.56)
Lagged price P_{t-1}(+)	-7.214	-174.239	280.763	28.289
	(-0.06)	***(-2.84)	(0.47)	(0.35)
Direction lagged D_{t-1}(-)	0.004	0.327	-1.394	-0.026
	(0.03)	***(3.32)	*(-1.95)	(-0.14)
Price P_t (-)	25.568	177.826	-405.219	22.400
	(0.20)	***(2.91)	(-0.72)	(0.27)
Inventory, lagged I_{it-1} (-)	-0.073	-0.901	-0.059	-0.185
	***(-3.44)	***(-10.96)	(-0.63)	***(-2.67)
Adjusted R^2	0.03	0.34	0.09	0.07
Durbin-Watson stat	2.64	2.04	2.28	1.83
Observations	452	255	48	144

Estimated by GMM and Newey-West correction. t-values in parenthesis, and “***”, “**” and “*” indicate significance at the 1%, 5% and 10%-level respectively.

Regressing outgoing trade on a constant, change in price, and inventory does not change any of the results.

5 Conclusion and future work

In this paper, we have studied the behavior of four interbank foreign exchange dealers. We have done this study with a detailed data set from March 1998, with transaction prices, trading quantities, dealer inventories, exact timing, and which trading system were used for the transaction. The four dealers trade in different exchange rates and have different trading styles. In particular, we study how and if dealers set prices to protect against private information (information effects), and how they control inventory to adjust their risk exposure.

In a widely cited paper, Lyons (1995), using data from 1992, found support for both information and inventory effects in the pricing of a market maker. The market maker of Lyons increased his spread to protect against private information, and adjusted the midpoint in the spread (quote shading) to induce trade in a preferred directions to adjust inventory. Using the same model as Lyons, the Madhavan and Smidt (1991)-model, we find no support for neither information nor inventory effects. We believe this is primarily due to the change in structure of the foreign exchange market. In 1992, most trading was bilateral direct trading through the electronic system Reuters D2000-1. Since then, the electronic brokers Reuters D2000-2 and EBS have gained popularity. Through these systems, dealers can see a larger share of the trading of the market. Hence, transparency may have increased, making individual trades less important for information updating. The electronic brokers may also have turned out to be more attractive options for inventory control.

First, the electronic brokers are very liquid systems, where the dealers do not have to shade quotes to control inventory. Second, outgoing trades through the electronic brokers may be a more attractive option for inventory control than outgoing trades in direct trading since the dealers stays anonymous on the electronic brokers.

When we study the quoted bid ask spreads from direct trading, we do find that spreads indeed widen with the size of transaction. This leads us to conclude that there is an information effect in direct trading. Lyons data were solely from direct trading, and the Madhavan and Smidt model is probably best suited to this kind of trading. We also find that the information effect is confirmed when we estimate the Madhavan and Smidt model for direct trades only.

When it comes to the electronic brokers, the conjecture that sequences of trades may be more informative than single trades is supported. We find that the cumulative order flow on the electronic brokers and exchange rates are cointegrated, with a higher price when the cumulative flow is high and positive. If there is a buying pressure of USD for DEM in the market, the DEM price for USD will be higher.

Introduction of the new electronic brokers means more options for controlling inventory not recognized in the theoretical model. The dealers can choose between shading quotes in direct trading (the traditional method), hitting others quotes either in direct trading or on the electronic brokers (indirect trading), or they can enter quotes on the electronic brokers. Lack of evidence of bid shading as a tool for inventory control should therefore not be surprising. We do find evidence that dealers use outgoing trades for controlling inventory. Trading outgoing is more likely when inventory is large in absolute value. Furthermore, the dealers sell in outgoing trades when they have large long positions, and buy in outgoing trades when they have large short positions.

Finally, the high share of outgoing trades for our dealers may indicate that they are more like "speculators," i.e. make money on rate changes, than "market makers" that make money on the bid ask spread.

It seems that the dealer Lyons studied had a trading style particularly well suited for analysis with the Madhavan and Smidt model. Lyons' dealer had a high share of incoming direct trades, and hence had to control inventory partly through quote-shading. Furthermore, the dealer worked in an investment bank, and did not see any customer order flow. The risk of revealing inventory was therefore not that crucial.

Our results indicate that the Madhavan and Smidt model is not that applicable to foreign exchange trading as first believed. The Madhavan and Smidt model focuses on the pricing decision of a market maker in incoming trades. With the new microstructure of the foreign exchange market, we believe that outgoing trades have become a more viable option for dealers. To understand the foreign exchange market we believe it is important to do research not only on the market makers decision but also on the aggressors decision (outgoing trade). New theories that address risk management and information updating in an trading environment with both direct and indirect trading are in great demand.

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A The final data set

The first part of the data set contains all transactions and internal transfers, thus enables us to compute the correct inventories. This part also contains all the electronically conducted trades. The second parts contains all electronically conducted transactions, and in particular contains information on which dealer made the initiative to the trade and on what system were used. To transfer this information to the data set with all transactions, we need to identify the electronic trades in the first part of the data set, i.e. match the two parts.

The following information is common in the two parts, and hence used for matching:

1. Date
2. Dealer
3. Currency bought
4. Currency Sold
5. Amount bought
6. Price
7. Amount sold

When we get a match we check that the codes for counterpart, which are not exactly identical in the two parts, and the time of transaction match as well. For all matches we use the time, initiator and system information from the electronic transactions. The time from the electronic files (part two) is more accurate than what is the case in the file to keep track of inventory (part one).

Some of the trades conducted electronically may be executed on behalf of another dealer, and should hence be credited the dealer that makes the decisions for the trade. We identify these trades by first do the matching without dealer name among the remaining trades, and then searching to see if we can find any internal transfer that also match. These internal transfer are in most cases right before or after in time to the transaction.

Finally, an order entered into the electronic brokers may be split into several transactions with different counterparts. We identify such combined transactions and collect them into one trade, by checking that two transactions on the same system with the same price, direction and currency cross should not be longer apart than 15 seconds. Table 21 summarizes some results from the building of the data set.

Table 21: Summary information on the creation of the data set

	Dealer 1	Dealer 2	Dealer 3	Dealer 4
Total	1144	559	615	871
No direction	80	13	168	109
Combined	151	45	29	83
Trades	913	501	418	679
Tested exchange rate	913	447	247	422

Further information about the data set can be obtained from the authors.

B Baseline model of Lyons (1995)

When it is a incoming trade we employ the setup from Lyons (1995).

$$Q_{jt} = \theta(\mu_{jt} - P_{it}) + X_{jt} \tag{B.1}$$
$$P_{it} = \mu_{it} - \alpha_I (I_{it} - I_i^*) + \gamma D_t. \tag{B.2}$$

To derive the price-schedule we need to insert for the expectations in (B.2) and (B.1). After observing the private signal C_{jt}, dealer j's posterior (μ_{jt}) can be expressed as:

$$\mu_{jt} = \lambda\mu_t + (1-\lambda)C_{jt}, \tag{B.3}$$

where $\lambda = \sigma_\omega^2/(\sigma_1^2 + \sigma_\omega^2)$. Dealer i conditions on various possible Q_{jt}'s, and sets prices that are ex post regret-free as in Glosten and Milgrom (1985). More specifically, dealer i forms the statistic Z_{jt} from the observed demand of j:[21]

$$Z_{jt} = \frac{Q_{jt}/\theta + P_{it} - \lambda\mu_t}{1-\lambda} = V_t + \omega_{jt} + \frac{1}{\theta(1-\lambda)} X_{jt}. \tag{B.4}$$

Equation (B.1) and (4) are used to derive the second equality. Z_{jt} is normally distributed with mean V_t and variance $\sigma_{Z_j}^2$ (equal to the variance of the two last terms). Furthermore, Z_{jt} is statistically independent of μ_t. Dealer i's posterior belief (μ_{it}) is a weighted average of μ_t and Z_{jt};

$$\mu_{it} = \kappa\mu_t + (1-\kappa) Z_{jt}, \tag{B.5}$$

where $\kappa = \sigma_{Zj}^2/(\sigma_1^2 + \sigma_{Zj}^2)$. Using the first equality in (B.4), we see that dealer i's posterior belief is expressed as a function of any Q_{jt}:

$$\mu_{it} = \phi\mu_t + (1-\phi)\left(\frac{Q_{jt}}{\theta} + P_{it}\right), \tag{B.6}$$

where $\phi = \kappa - \lambda(1-\kappa)/(1-\lambda)$, a weight-parameter from the Bayesian updating that makes the quote regret-free. $\phi \in [0,1]$ and we can write the coefficients as a sum equal one since

$$\kappa - \frac{\lambda(1-\kappa)}{1-\lambda} + \frac{1-\kappa}{1-\lambda} = \frac{\kappa(1-\lambda) - \lambda(1-\kappa) + 1 - \kappa}{1-\lambda} = 1$$

Inserting (B.6) into (B.2) gives:

$$P_{it} = \phi\mu_t + (1-\phi)\left(\frac{Q_{jt}}{\theta} + P_{it}\right) - \alpha(I_{it} - I_i^*) + \gamma D_t$$
$$\Rightarrow P_{it}[1-(1-\phi)] = P_{it}\phi = \phi\mu_t + \frac{(1-\phi)}{\theta} Q_{jt} - \alpha(I_{it} - I_i^*) + \gamma D_t$$
$$P_{it} = \mu_t + \frac{1-\phi}{\phi\theta} Q_{jt} - \frac{\alpha}{\phi}(I_{it} - I_i^*) + \frac{\gamma}{\phi} D_t. \tag{B.7}$$

[21] Actual demand Q_{jt}, θ and the traded price P_{it} is observable to dealer i. In addition dealer i also knows the common prior and the variances of the signals. Z_{jt} is then derived as follows,

$$Q_{jt}/\theta + P_{it} = \mu_{jt} + X_{jt}/\theta = \lambda\mu_t + (1-\lambda)C_{jt} + X_{jt}/\theta$$

Subtracting $\lambda\mu_t$ on both sides and dividing through with $(1-\lambda)$ gives an unbiased estimate of C_{jt}.

To test this equation, we need to replace μ_t, which is unobservable to the econometrician. To overcome this problem we use that the only difference between this period's prior and the last period's belief is the (stochastic) public information r_{t-1}. We can therefore write the prior as last period's belief plus an expectational error term ε_{it}.

$$\mu_t = \mu_{it-1} + \varepsilon_{it}$$

From the behavioral assumptions we can find an action corresponding to belief μ_{it-1} and substitute this for μ_{it-1},

$$\mu_t = P_{it-1} + \alpha\left(I_{it-1} - I_i^*\right) - \gamma D_{t-1} + \varepsilon_{it}. \tag{B.8}$$

Substituting this expression for μ_t into (B.7), gives

$$\Delta P_{it} = \alpha\left(\frac{1}{\phi} - 1\right) I_i^* + \frac{1-\phi}{\phi\theta} Q_{jt} - \frac{\alpha}{\phi} I_{it} + \alpha I_{it-1} + \frac{\gamma}{\phi} D_t - \gamma D_{t-1} + \varepsilon_{it}. \tag{B.9}$$

Thus, the benchmark model to test is:

$$\Delta P_{it} = \beta_0 + \beta_1 Q_{jt} + \beta_2 I_{it} + \beta_3 I_{it-1} + \beta_4 D_t + \beta_5 D_{t-1} + \varepsilon_{it}. \tag{B.10}$$

The model predicts that $\{\beta_1, \beta_3, \beta_4\} > 0, \{\beta_2, \beta_5\} < 0,\ |\beta_2| > \beta_3,\ \beta_4 > |\beta_5|$. The latter inequalities derive from the fact that $0 < \phi < 1$.

Since the error term ε_{it} is interpreted as an expectational error between period t and $t-1$ it will be related to last periods expectation, which again influences the pricing decision in that period. The error term will therefore have a dynamic structure:

$$\begin{aligned}
\varepsilon_{it} &= \mu_t - \mu_{it-1} \\
\mu_t &= V_t + \eta_t \\
\mu_{it-1} &= \kappa \mu_{t-1} + (1-\kappa) Z_{jt-1} \\
&= \kappa\left(V_{t-1} + \eta_{t-1}\right) + (1-\kappa)\left[V_{t-1} + \omega_{jt-1} + \frac{1}{\theta(1-\lambda)} X_{jt-1}\right] \\
&= V_{t-1} + \kappa\eta_{t-1} + (1-\kappa)\left[\omega_{jt-1} + \frac{1}{\theta(1-\lambda)} X_{jt-1}\right] \\
\Rightarrow \varepsilon_{it} &= V_t + \eta_t - V_{t-1} - \kappa\eta_{t-1} - (1-\kappa)\left[\omega_{jt-1} + \frac{1}{\theta(1-\lambda)} X_{jt-1}\right]
\end{aligned}$$

The properties of the error term:

$$E\left[\varepsilon_{it}\right] = E\left[V_t - V_{t-1}\right] = 0$$

$$E\left[\varepsilon_{it}\varepsilon_{it-s}\right] = \begin{cases} \left(1+\kappa^2\right)\sigma_1^2 + (1-\kappa)^2\left[\sigma_\omega^2 + \left(\frac{1}{\theta(1-\lambda)}\right)^2 \sigma_X^2\right] & \text{when } s = 0 \\ -\kappa\sigma_1^2 & \text{when } s = 1 \\ 0 & \text{when } s > 1 \end{cases}$$

We can write the error term as a MA(1) process,

$$\varepsilon_{it} = \beta_6 \nu_{t-1} + \nu_t,\ \beta_6 < 0 \tag{B.11}$$

where $\nu_t \sim \text{IID}\left(0, \sigma_\nu^2\right)$. These properties will be the same for all the models.

C Direct and indirect trading

As argued earlier, trades conducted directly carry probably more information than those conducted indirectly. Hence, we let the updated belief depend on the system used for the trade in the following way

$$\mu_{it} = d_t \left[\kappa^{D}\mu_t + \left(1-\kappa^{D}\right) Z_{jt}\right] + (1-d_t)\left[\kappa^{I}\mu_t + \left(1-\kappa^{I}\right) Z_{jt}\right], \tag{C.1}$$

where d_t is a dummy that equals 1 if the trade is a direct, and 0 if the trade is indirect. κ^{D} and κ^{I} are the weights on prior belief when the trade is direct or indirect respectively. The hypothesis is that Z_{jt} is a more precise signal in direct trades, and hence $\kappa^{D} < \kappa^{I}$. This implies $\phi^{D} < \phi^{I}$, which means that the information effect is smaller for indirect trade. We see this from differentiating the coefficient to Q_{jt} with respect to ϕ, which gives

$$\frac{-\phi\theta-(1-\phi)\theta}{(\phi\theta)^2} = \frac{-1}{\phi^2\theta} < 0$$

Updated beliefs can be written as

$$\begin{aligned}
\mu_{it} &= \left[d_t\kappa^{D} + (1-d_t)\kappa^{I}\right]\mu_t + \left[d_t\left(1-\kappa^{D}\right) + (1-d_t)\left(1-\kappa^{I}\right)\right] Z_{jt} \\
&= \left[d_t\kappa^{D} + (1-d_t)\kappa^{I}\right]\mu_t + \frac{d_t\left(1-\kappa^{D}\right) + (1-d_t)\left(1-\kappa^{I}\right)}{1-\lambda}\left(\frac{Q_{jt}}{\theta} + P_{it} - \lambda\mu_t\right) \\
&= \left\{d_t\left[\kappa^{D} - \frac{\left(1-\kappa^{D}\right)\lambda}{1-\lambda}\right] + (1-d_t)\left[\kappa^{I} - \frac{\left(1-\kappa^{I}\right)\lambda}{1-\lambda}\right]\right\}\mu_t \\
&\quad + \left\{d_t\frac{1-\kappa^{D}}{1-\lambda} + (1-d_t)\frac{1-\kappa^{I}}{1-\lambda}\right\}\left(\frac{Q_{jt}}{\theta} + P_{it}\right) \\
&= \left[d_t\phi^{D} + (1-d_t)\phi^{I}\right]\mu_t + \left[d_t\left(1-\phi^{D}\right) + (1-d_t)\left(1-\phi^{I}\right)\right]\left(\frac{Q_{jt}}{\theta} + P_{it}\right)
\end{aligned} \tag{C.2}$$

ϕ^{D} and ϕ^{I} are defined similar as in the benchmark case.

It might be that dealers shade quotes differently on different systems, either that they shade more on indirect trading because they do not reveal their position, or shade less because the market is more liquid and hence making shading less needed. In this case we postulate the following equation:

$$P_{it} = \mu_{it} - \left[\alpha^{D}d_t + \alpha^{I}(1-d_t)\right](I_{it} - I_i^*) + \gamma D_t. \tag{C.3}$$

We now combine the two mechanisms, differences both in information and inventory control across the two systems. This imply using the following equations:

$$\begin{gathered}
\mu_{it} = d_t\left[\kappa^{D}\mu_t + \left(1-\kappa^{D}\right)Z_{jt}\right] + (1-d_t)\left[\kappa^{I}\mu_t + \left(1-\kappa^{I}\right)Z_{jt}\right] \\
P_{it} = \mu_{it} - \left[\alpha^{D}d_t + \alpha^{I}(1-d_t)\right](I_{it} - I_i^*) + \gamma D_t. \\
\mu_t = P_{it-1} + \left[\alpha^{D}d_{t-1} + \alpha^{I}(1-d_{t-1})\right](I_{it-1} - I_i^*) - \gamma D_{t-1} + \varepsilon_{it}
\end{gathered}$$

The pricing schedule then becomes:

$$P_{it} = \mu_t + \frac{1-\left[d_t\phi^{D} + (1-d_t)\phi^{I}\right]}{\left[d_t\phi^{D} + (1-d_t)\phi^{I}\right]\theta}Q_{jt} - \frac{\alpha^{D}d_t + \alpha^{I}(1-d_t)}{d_t\phi^{D} + (1-d_t)\phi^{I}}(I_{it} - I_i^*) + \frac{\gamma}{d_t\phi^{D} + (1-d_t)\phi^{I}}D_t$$

It is easier to work with if we rewrite the coefficients containing dummies:

$$\frac{1-\left[d_t\phi^{\mathrm{D}}+(1-d_t)\,\phi^{\mathrm{I}}\right]}{\left[d_t\phi^{\mathrm{D}}+(1-d_t)\,\phi^{\mathrm{I}}\right]\theta}=\begin{cases}\dfrac{1-\phi^{\mathrm{D}}}{\phi^{\mathrm{D}}\theta} & \text{when } d_t=1\\ \dfrac{1-\phi^{\mathrm{I}}}{\phi^{\mathrm{I}}\theta} & \text{when } d_t=0\end{cases}$$

$$\frac{\alpha^{\mathrm{D}}d_t+\alpha^{\mathrm{I}}(1-d_t)}{d_t\phi^{\mathrm{D}}+(1-d_t)\,\phi^{\mathrm{I}}}=\begin{cases}\dfrac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}} & \text{when } d_t=1\\ \dfrac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}} & \text{when } d_t=0\end{cases}$$

$$\frac{\gamma}{d_t\phi^{\mathrm{D}}+(1-d_t)\,\phi^{\mathrm{I}}}=\begin{cases}\dfrac{\gamma}{\phi^{\mathrm{D}}} & \text{when } d_t=1\\ \dfrac{\gamma}{\phi^{\mathrm{I}}} & \text{when } d_t=0\end{cases}$$

This gives us

$$P_{it}=\mu_t+\left[\frac{1-\phi^{\mathrm{D}}}{\phi^{\mathrm{D}}\theta}d_t+\frac{1-\phi^{\mathrm{I}}}{\phi^{\mathrm{I}}\theta}(1-d_t)\right]Q_{jt} \\ -\left[\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}}d_t+\frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}}(1-d_t)\right](I_{it}-I_i^*)+\left[\frac{\gamma}{\phi^{\mathrm{D}}}d_t+\frac{\gamma}{\phi^{\mathrm{I}}}(1-d_t)\right]D_t \quad \text{(C.4)}$$

To get an estimable equation we insert the expectation:

$$P_{it}=P_{it-1}+\left[\alpha^{\mathrm{D}}d_{t-1}+\alpha^{\mathrm{I}}(1-d_{t-1})\right](I_{it-1}-I_i^*)-\gamma D_{t-1}+\left[\frac{1-\phi^{\mathrm{D}}}{\phi^{\mathrm{D}}\theta}d_t+\frac{1-\phi^{\mathrm{I}}}{\phi^{\mathrm{I}}\theta}(1-d_t)\right]Q_{jt} \\ -\left[\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}}d_t+\frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}}(1-d_t)\right](I_{it}-I_i^*)+\left[\frac{\gamma}{\phi^{\mathrm{D}}}d_t+\frac{\gamma}{\phi^{\mathrm{I}}}(1-d_t)\right]D_t+\varepsilon_{it}$$

Collecting terms:

$$\Delta P_{it}=\left[\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}}d_t+\frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}}(1-d_t)\right]I_i^*-\left[\alpha^{\mathrm{D}}d_{t-1}+\alpha^{\mathrm{I}}(1-d_{t-1})\right]I_i^*+\left[\frac{1-\phi^{\mathrm{D}}}{\phi^{\mathrm{D}}\theta}d_t+\frac{1-\phi^{\mathrm{I}}}{\phi^{\mathrm{I}}\theta}(1-d_t)\right]Q_{jt} \\ -\left[\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}}d_t+\frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}}(1-d_t)\right]I_{it}+\left[\alpha^{\mathrm{D}}d_{t-1}+\alpha^{\mathrm{I}}(1-d_{t-1})\right]I_{it-1}+\left[\frac{\gamma}{\phi^{\mathrm{D}}}d_t+\frac{\gamma}{\phi^{\mathrm{I}}}(1-d_t)\right]D_t-\gamma D_{t-1}+\varepsilon_{it} \quad \text{(C.5)}$$

Econometric equation:

$$\Delta P_{it}=\beta_0+\beta_0'd_t+\beta_0''d_{t-1}+\beta_1^{\mathrm{D}}d_tQ_{jt}+\beta_1^{\mathrm{I}}(1-d_t)\,Q_{jt} \\ +\beta_2^{\mathrm{D}}d_tI_{it}+\beta_2^{\mathrm{I}}(1-d_t)\,I_{it}+\beta_3^{\mathrm{D}}d_{t-1}I_{it-1}+\beta_3^{\mathrm{I}}(1-d_{t-1})\,I_{it-1} \\ +\beta_4^{\mathrm{D}}d_tD_t+\beta_4^{\mathrm{I}}(1-d_t)\,D_t+\beta_5D_{t-1}+\varepsilon_{it} \quad \text{(C.6)}$$

Regression coefficients:

$$
\begin{aligned}
\beta_0 &= \alpha^{\mathrm{I}}\left(\frac{1}{\phi^{\mathrm{I}}}-1\right)I_i^* \approx 0 &\quad \beta_0' &= \left(\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}}-\frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}}\right)I_i^* \approx 0\\
\beta_0'' &= -\left(\alpha^{\mathrm{D}}-\alpha^{\mathrm{I}}\right)I_i^* \approx 0 & \beta_1^{\mathrm{D}} &= \frac{1-\phi^{\mathrm{D}}}{\phi^{\mathrm{D}}\theta} > 0\\
\beta_1^{\mathrm{I}} &= \frac{1-\phi^{\mathrm{I}}}{\phi^{\mathrm{I}}\theta} > 0 & \beta_2^{\mathrm{D}} &= -\frac{\alpha^{\mathrm{D}}}{\phi^{\mathrm{D}}} < 0\\
\beta_2^{\mathrm{I}} &= -\frac{\alpha^{\mathrm{I}}}{\phi^{\mathrm{I}}} < 0 & \beta_3^{\mathrm{D}} &= \alpha^{\mathrm{D}} > 0\\
\beta_3^{\mathrm{I}} &= \alpha^{\mathrm{I}} > 0 & \beta_4^{\mathrm{D}} &= \frac{\gamma}{\phi^{\mathrm{D}}} > 0\\
\beta_4^{\mathrm{I}} &= \frac{\gamma}{\phi^{\mathrm{I}}} > 0 & \beta_5 &= -\gamma < 0
\end{aligned}
\tag{C.7}
$$

The coefficients β_1^{D} and β_1^{I} capture information effect, while β_3^{D} and β_3^{I} capture inventory control. The coefficient β_5 is the same as in the benchmark model, β_1^{D}.