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Optimal Transparency in a Dealer Market with an Application to Foreign Exchange*

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This paper addresses a fundamental trade-off in the design of multiple-dealer markets. Namely, though greater transparency can accelerate revelation of information in price, it can also impede dealer risk management. If dealers could choose the transparency regime ex ante, which regime would they choose? We show that dealers prefer incomplete transparency (meaning marketwide order flow is observed with noise). Slower price adjustment provides time for nondealers to trade, thereby sharing risk otherwise borne by dealers. At some point, however, further reduction in transparency impedes risk sharing: too noisy a public signal provides nondealers too little information to induce them to trade. *Journal of Economic Literature* Classification Numbers: F31, G15.

This paper addresses transparency of the trading process. Determining which participants see what, and when, is central to the design of multiple-dealer markets. At a broad level, policymakers are concerned with the following trade-off: though greater transparency can accelerate revelation of information in price, it can also impede dealer risk management.[1] Indeed, Board and Sutcliffe (1995) write that "the purpose of a transparency regime

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[1] One reason greater transparency might not accelerate revelation in price involves incentives for acquiring new information. That is, greater transparency might reduce these incentives. In our judgment, however, this is unlikely to be relevant in the foreign exchange market.

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is to allow marketmakers to offset inventory risk by trading before the market as a whole is aware of the large trade." In equity markets, the transparency regime is typically imposed (e.g., the London Stock Exchange and NASDAQ). On the London Stock Exchange, for example, smaller trades must be published within three minutes, while publication of the largest trades can be delayed up to five business days. In contrast, spot foreign exchange (FX) imposes no publication requirements. For this reason, FX is particularly interesting since its degree of transparency has arisen without regulatory influence.

Our objective is to clarify optimal transparency from the dealer perspective. We make no claim that this narrow view corresponds to optimality in a broader sense. The dealer perspective is key, however, to understanding the transparency regimes in today's markets, especially where unregulated. Since FX is a prime example, we employ a dealing model with a trading structure like that in FX. A key feature is that dealers face unavoidable position disturbances. We show that the risk of these disturbances can be more difficult to manage with greater transparency. Thus, our model generates the effect cited above, namely that greater transparency accelerates the revelation of information in price, leaving dealers less time for position management. Though not framed in a microstructural context, Hirshleifer (1971) provides one way to understand this effect of faster revelation: he shows that in general, additional ex ante information can impede risk sharing.

The specific question we examine is the following: If dealers could choose the transparency regime ex ante, which regime would they choose? We show that dealers prefer incomplete transparency. Here, incomplete transparency means that marketwide order flow is observed with noise. This noisy signal slows price adjustment, which provides time for nondealers to trade, thereby sharing risk otherwise borne by dealers. Dealers do not, however, prefer a complete lack of transparency. At some point, further reduction in transparency begins to impede risk sharing. This is because too noisy a public signal provides nondealers too little information to trade, and if they do not trade, they share no risk. Thus, the Hirshleifer (1971) effect noted above is not the whole story: some order-flow information is necessary to induce nondealer participation.

There are several features of the FX market that influence our specification of the dealing model. For example, interdealer trading accounts for about 85% of volume in this market (see NY Fed, 1992). Accordingly, we focus attention at the dealer level. Customers of dealer services are atomistic in the model, and therefore behave competitively. The strategic interaction occurs between dealers. This interdealer focus is motivated by more than just the 85% share of interdealer trading in FX. For example, since in reality customers far outnumber dealers, intermediation concentrates order-flow information at the dealer level, which concentrates the adverse-selection problem at that level (see Lyons, 1996). Also, in FX, an individual customer with substantial private information is not realistic under normal circumstances. Though it is tempting to offer central bank intervention as a counter-example, intervention is in fact rare in the biggest spot markets (all of which involve the dollar). Moreover, when intervention does occur, it is small relative to total volume, and its monetary effect is typically sterilized. (Exceptions do exist, of course. One example is the smaller cross-rate markets within the European Monetary System, where intervention or the threat thereof is indeed significant.)

The model includes information asymmetry and risk aversion. Both are clearly necessary to generate links between the pace of revelation and the amount of risk sharing. Papers that address transparency using distinctly different models include Wolinsky (1990), Roell (1992), Madhavan (1993), Pagano and Roell (1993), and Biais (1993). All but the last of these papers include information asymmetry, but omit risk aversion. The model of Biais (1993) incorporates risk aversion, but omits private information. Further, interdealer trading never occurs in most of these models, whereas here it is the focus. The model nearest in spirit to ours is that of Naik *et al.* (1994). Their focus, however, is the transparency of customer–dealer trades. This contrasts sharply with our focus on transparency of interdealer trades (with unobservable customer–dealer trades). While the transparency of customer–dealer trades is relevant for equities, in FX customer–dealer trades are never publicly observable. Thus, in FX it is the transparency of interdealer activity that drives price formation.

The paper is organized as follows: Section I presents the dealing model. Section II determines a set of Bayesian–Nash equilibria, the elements of which are indexed by the transparency of order flow. Section III addresses the dealers' preferred equilibrium from the set determined in the previous section. Section IV provides institutional detail on the FX market, and Section V concludes.

I. THE MODEL

First we outline the general features of our dealing model, which draws from Lyons (1996). We refer to it as a "simultaneous trade" model, to distinguish it from more familiar sequential trade models (Glosten and Milgrom, 1985) and auction models (Kyle, 1985). The term simultaneous trade captures our modeling of trade among dealers as a game with simultaneous and independent moves. Specifically, when determining their trades dealers cannot condition on the trades of other dealers that occur in the same period. This simultaneous trade feature has the advantage that it integrates position disturbances and dealing in a natural way. A more precise definition of the model's structure follows the outline.

A. *General Features of the Model*

There are two types of agents in the market for a single risky asset, dealers and customers, where customers comprise all nondealer participants. (In FX, customers include corporate treasurers, investors, speculators, liquidity traders, central banks, etc.) Customers are atomistic, and therefore behave competitively, whereas dealers behave strategically. In each of two periods, there are four events:

Event 1. Each dealer quotes a single price that is observable and available to all customers and dealers.

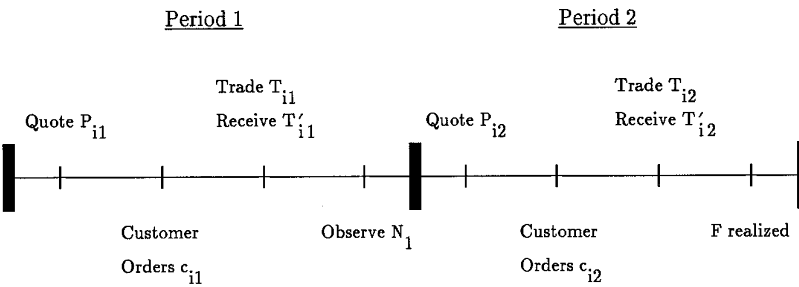
Event 2. Each dealer then accommodates customer market-orders. A distinct set of customers, or customer base, is linked to each dealer. The customer trades of other dealers are not observable. Because customer order flow is informative, this produces asymmetric information among dealers.

Event 3. Dealers then trade among themselves. The order flow from interdealer trading in period one—to the extent it is observable—drives the determination of period-two quotes.

Event 4. The last event in each period involves public information. In period one a signal of net interdealer order flow is observed, and in period two the full-information value itself is revealed.

Figure 1 provides an overview of the events, and summarizes the information available to dealers for quoting and trading in each period. The notation introduced in Fig. 1 is clarified below.

An important feature of the model is that customer order flow in period one is different in nature than that in period two. The intent is to capture the reality that customer activity in markets like FX exhibits bursts of trading. These bursts affect the variability of dealer positions. Accordingly, in period one, each dealer receives random customer orders that both disturb the dealer's position and provide information. Period two, in contrast, is the tranquil period with respect to customer orders: customers are induced to trade only if the risky asset yields a sufficient return conditional on information available to them. Given preferences, this implies that period-two customer trades are a deterministic linear function of any bias in price. This generates a risk-sharing role for customers in period two. This risk-sharing role is central to our results.



Information set for:

Quoting $P_{i1} \equiv \Omega_{Pi1} = \{E[F]=0\}$

Trading $T_{i1} \equiv \Omega_{Ti1} = \{E[F]=0, P_{11}, \ldots, P_{n1}, c_{i1}\}$

Quoting $P_{i2} \equiv \Omega_{Pi2} = \{E[F]=0, P_{11}, \ldots, P_{n1}, c_{i1}, T_{i1}, T'_{i1}, N_1\}$

Trading $T_{i2} \equiv \Omega_{Ti2} = \{E[F]=0, P_{11}, \ldots, P_{n1}, c_{i1}, T_{i1}, T'_{i1}, N_1, P_{12}, \ldots, P_{n2}, c_{i2}\}$

FIG. 1. Timing of events and information sets. The top panel presents the timing of events. The bottom panel presents the information sets available to the dealer at each of the four decision nodes, two quoting and two trading. Definitions: P_{it} is dealer i's quote in period t, which applies to both customer and interdealer trades. c_{it} is incoming customer orders (net) received by dealer i in period t. T'_{it} is incoming dealer orders (net) received by dealer i in period t. T_{it} is dealer i's outgoing interdealer orders (net). The orders c_{it}, T'_{it}, and T_{it} are positive if the aggressor is buying, negative if the aggressor is selling. N_1 is the public signal of period-one interdealer order flow (net). F is the full information value of the risky asset, realized at the close of period two.

B. *Specifics of the Model*

The model is a two-period game with n dealers. Each dealer has an equal-sized customer base composed of nonstrategic customers. All dealers and customers have identical negative exponential utility defined over final wealth. There are two assets, one risky and one riskless, whose returns are realized at the close of period 2. The gross return on the riskless asset is normalized to one. The risky asset is in zero supply initially, and has a random full-information value F. (Assuming nonzero initial supply does not affect the results; it simply requires bias in initial prices to induce agents to hold the supply.)

Event 1: Dealer Quoting. At the outset of each period dealers quote prices. Let P_{it} denote the quote of dealer i in period t. The four rules governing each P_{it} are the following:

(R1) Quotes are observable and available to all customers and dealers.

(R2) Each quote is a single price at which the dealer agrees both to buy and sell.

(R3) Quotes are good for any size.[2]

(R4) Dealers cannot refuse to quote.

This last rule is particularly relevant in period two when a dealer with a near-zero customer order in period one—and therefore little information—would choose to exit if possible. In reality, in FX those who breach the implicit contract of reciprocity in providing quotes are punished by other dealers (e.g., by refusing to provide subsequent quotes, or by quoting large spreads).

Event 2: Customer Orders and a Definition of the Information Structure. Private information at the dealer level is determined by the customer market orders each receives in period one. One rationale (among many) for informative customer orders that is relevant for FX involves net export performance. That is, an important component of standard models of exchange rate fundamentals is the trade balance. A country's trade balance, in turn, is simply an aggregation of transactions at the firm level. These transactions generate liquidity trades that, when aggregated, provide a signal of the trade-balance component of fundamentals (and do so long before published statistics are available). Consistent with this, we write[3]

$$\tilde{F} = \sum_{i=1}^{n} \tilde{c}_{i1} + \tilde{v}, \tag{1}$$

where F here is the full-information value of the risky asset, and c_{i1} denotes

[2] Relative to other markets, the size tradable at quoted prices in FX are huge. Among the larger dealers, DM/$ quotes are good for $10 million. See also Pithyachariyakul (1986) and Mendelson (1987) for transaction prices that are independent of order size.

[3] Empirically, Lyons (1995) finds that order flow has significant information effects on prices in the FX market. The model introduced in Lyons (1996) provides a much richer information structure. For the issue at hand, the added complexity adds nothing.

the *net* of the signed customer orders received by dealer i in period one (c_{i1} executes at P_{i1} for all i). The c_{i1}'s and the noise ν are independently and normally distributed about zero with variances Σ_ν and Σ_c, respectively.[4] (We use the convention that c_{it} is positive for customer purchases, and negative for sales.) This specification implies that before customer orders are received, each dealer's prior expectation of the full-information value is zero; after receiving c_{i1}, each dealer has some private information.

There are no random customer trades in period two. Deterministic customer trades can arise however: with exponential utility, the net period-two customer order for each dealer is a linear function of any bias in period-two prices:

$$c_{i2} = \zeta(E[F \mid \Omega_{C2}] - P_{i2}). \tag{2}$$

Here, $\Omega_{C2} \equiv \{P_{11}, \dots, P_{n1}, N_1, P_{12}, \dots, P_{n2}\}$ is the public information available to customers for trading in period two, where N_1 is a signal of net interdealer volume in period one (defined below). The constant ζ is common to each dealer, and is a combination of (i) the coefficient of risk aversion, (ii) the variance of the period-two return conditional on Ω_{C2}, and (iii) the mass of customers in each customer base. ζ approaches infinity as the mass of customers in each customer base approaches infinity. We assume each customer base is the same size.

Event 3: Interdealer Trading Protocol. Event 3 in both periods is interdealer trading. Interdealer trading occurs at the prices quoted at Event 1. Let T_{it} denote the outgoing interdealer orders placed by dealer i in period t (net); let T'_{it} denote the incoming interdealer orders received by dealer i in period t (net). There are three rules governing interdealer trading. For the third—the trade allocation rule—consider the dealers as arranged in a circle.

(R5) Trading is simultaneous and independent; dealers cannot condition on other dealers' trades when determining their own.[5]

(R6) Trading with multiple partners is feasible.

(R7) If a dealer wants to trade at a price for which he has received multiple quotes, he chooses the nearest one on the left.

Rule (R5) introduces the simultaneous trade feature of the model (in

[4] Though assuming mean zero c_{i1}'s might appear strong, in equilibrium dealer quotes in period one will be common and unbiased conditional on public information.

[5] Simultaneous moves are consistent with the fact that transactions in spot FX are typically initiated electronically rather than verbally, providing the capacity for simultaneous quotes, trades, or both. Here, a period should be viewed as the time it takes to make a trade, a span measured in seconds rather than hours, days, or weeks.

contrast with the sequential trade model of Glosten and Milgrom, 1985). This rule generates an important role for T'_{it}: Because interdealer trading is simultaneous and independent, T'_{it} is an unavoidable disturbance to dealer i's position, and this must be carried into the next period. The trade allocation rule (R7) is less restrictive than it may appear. In fact, faced with equal quotes, a dealer will be indifferent in equilibrium regarding which quote he chooses. (It is straightforward to allow a splitting of trades, as long as the number of pieces is known. If not known, however, this generates a nonnormal position disturbance. Moreover, splitting will not affect the average position disturbance faced by dealers, which is the key for determining how customers share risk in period two, as demonstrated below.)

Interdealer trades necessarily have multiple components. First, there is a speculative demand component driven by order-flow information. Let D_{it} denote this speculative demand by dealer i in period t. Second, for a dealer to achieve a net position of D_{it}, this period's customer orders must be laid off in interdealer trading. Third, in targeting D_{it}, dealers must account for the expected value of any incoming interdealer trades T'_{it}. Finally, in period two the realized period-one position must be offset, and this position has both a desired component D_{i1} and a disturbance component $T'_{i1} - E[T'_{i1} | \Omega_{Ti1}]$. Putting this together, we have

$$T_{i1} = D_{i1} + c_{i1} + E[T'_{i1} | \Omega_{Ti1}] \tag{3}$$

$$T_{i2} = D_{i2} + c_{i2} - D_{i1} + (T'_{i1} - E[T'_{i1} | \Omega_{Ti1}]) + E[T'_{i2} | \Omega_{Ti2}]. \tag{4}$$

The convention we use is that orders are signed according to the party that initiates the trade. Thus, T_{it} is positive for dealer i purchases, and positive c_{it}'s and T'_{it}'s correspond to dealer i sales.

Event 4: Defining a Transparency Regime. We define a transparency regime as follows. The last event in period one is a public signal of the signed interdealer order flow from period one. Let N_1 denote this signal. The precision of this signal determines the transparency regime. That is,

$$N_1 \equiv \sum_{i=1}^{n} T_{i1} + \tilde{\varepsilon}, \tag{5}$$

where the random variable ε is normally distributed with zero mean and known variance Σ_ε. Σ_ε, then, indexes the transparency regime.

Equation (5) defines transparency in terms of post-trade order flow information. This dimension of transparency is key for the design of multiple-dealer markets and is at the center of current policy debates. In the FX market, even without an imposed level of transparency, dealers do get signals of marketwide order flow that fit into this signal framework. Section IV examines these institutional features in more detail.

Dealer Optimization. We turn now to the dealers' problem.

$$\underset{\substack{P_{i1},P_{i2}\\T_{i1},T_{i2}}}{\text{Max}}\ E[-\exp(-\theta W_{i2})\,|\,\Omega_i]$$

$$\begin{aligned}\text{s.t. } W_{i2} = W_{i0} &+ (D_{i1} + E[T'_{i1}\,|\,\Omega_{Ti1}])(P'_{i2} - P'_{i1})\\ &+ (D_{i2} + E[T'_{i2}\,|\,\Omega_{Ti2}])(F - P'_{i2})\\ &- c_{i1}(P'_{i1} - P_{i1}) - c_{i2}(P'_{i2} - P_{i2}) - T'_{i1}(P'_{i2} - P_{i1}) - T'_{i2}(F - P_{i2}).\end{aligned} \tag{6}$$

Here, W_{it} denotes dealer i's end-of-period t wealth, P_{i1} denotes dealer i's period-one quote, and a $'$ denotes the incoming quote or trade received by dealer i. The information in Ω_i available for each of these decisions is presented in Fig. 1. The terms $T'_{i1}(P'_{i2} - P_{i1})$ and $T'_{i2}(F - P_{i2})$ in final wealth correspond to the position disturbances that arise from interdealer trading.

First, we solve for a linear, Bayesian–Nash equilibrium (BNE) conditional on each transparency regime. This solution incorporates the dealers' ability to influence period-two prices through their period-one trades (via the order flow signal N_1). Then, we solve for what we call the *dealer-optimal* BNE. This is the BNE corresponding to the transparency regime the dealers prefer most, in an ex ante sense. Put differently, if the representative dealer were asked which transparency regime she preferred to trade under, she would respond with the dealer-optimal BNE.

II. DETERMINING BAYESIAN–NASH EQUILIBRIA

To determine the linear BNE for each transparency regime, first we identify some properties of optimal quoting strategies. The following proposition shows that period-one quotes are equal across dealers. Let P_1 denote this quote.

PROPOSITION 1. *A quoting strategy is consistent with BNE only if the period-one quoted price* $P_{i1} = 0$, *for all* $i \in \{1, \ldots, n\}$.

Proof. Rational quotes must be common to avoid arbitrage in interdealer trading. This follows from quoting rules (R1)–(R4), trading rules (R5)–(R6), and risk-aversion. Unbiasedness is necessary to ensure that expected interdealer trades net to zero, which is necessary since dealers trade among themselves at event 3 in period one. Suppose not. Consider Eq. (3): if the common quote is biased conditional on public information, then $E[T'_{i1}|P_1] \neq 0$ since $E[D_{j1}|P_1] \neq 0$, where D_{j1} denotes the desired dealer demand implicit in T'_{i1}. This induces each dealer to adjust T_{i1} to offset the expected effect on his position. Any across-the-board adjustment in T_{i1}, however, increases the absolute magnitude of the expected T'_{i1} one-for-one. It is therefore impossible for dealers to offset the expected incoming order induced by the bias in price. Finally, $P_1 = 0$ since $E[F] = 0$. (With common prices, the level necessarily depends only on commonly observed information.)

There are two important implications of this common quote. First, from trading rule (R7), each dealer receives exactly one interdealer order in period one. This order is the position disturbance T'_{i1} in the dealer's problem in Eq. (6). Second, common period-one quotes imply that the $c_{i1}(P'_{i1} - P_{i1})$ and $E[T'_{i1}|\Omega_{Ti1}]$ terms in final wealth (Eq. 6) are equal to zero (the latter following from the lack of bias in P_1 and the lack of correlation across customer orders). These two implications also apply in period two, since optimal period-two quotes are common as well. The next proposition establishes this.

PROPOSITION 2. *A quoting strategy is consistent with BNE only if for all* $i \in \{1, \ldots, n\}$, *the price quoted in period two*, P_2, *is such that* $c_{i2} = -E[D_{i2} + c_{i1}|P_1, N_1, P_2]$.

Proof. The necessity of common quotes follows directly from the Proof of Proposition 1 (no arbitrage). The necessity that $c_{i2} = -E[D_{i2} + c_{i1}|P_1, N_1, P_2]$ for all i follows from the fact that any other level of period-two customer orders would result in expected interdealer trades that do not net to zero, which is incompatible with equilibrium by the same reasoning as that in the Proof of Proposition 1. To see that this level of customer orders is necessary, note from Eq. (4) that expected interdealer trades net to zero only if $E[D_{j2} + c_{j2} + T'_{j1} - D_{j1}|P_1, N_1, P_2] = 0$ (where again the subscript j denotes the dealer j components implicit in T'_{i2}). Thus, only a P_2 such that $c_{j2} = - E[D_{j2} + T'_{j1} - D_{j1}|P_1, N_1, P_2]$ can be an equilibrium (where c_{j2} is outside the expectations operator because, by assumption, it is a deterministic function of any bias conditional on information available to customers). Symmetry ensures that $E[D_{j2}|P_1, N_1, P_2] = E[D_{i2}|P_1, N_1, P_2]$, and that $E[T'_{j1} - D_{j1}|P_1, N_1, P_2] = E[c_{i1}|P_1, N_1, P_2]$. Since the customer bases are equal sized, c_{i2} is the same for all i.

Proposition 2 is important for our results because it shows the degree to which customers share risk in period two. The key is that P_2 necessarily settles at a level where customers are induced to absorb dealer position disturbances from period-one's interdealer trading. To see this, note from the previous proof that at P_2: $c_{i2} + E[D_{i2}|P_1, N_1, P_2] = -E[c_{i1}|P_1, N_1, P_2]$. Thus, c_{i2} and D_{i2} share in absorbing an estimate of the average customer trade in period one. The absorption provided by customers via c_{i2} is a function of the precision of $E[c_{i1}|P_1, N_1, P_2]$, which is clearly driven by the information in N_1. The information in N_1, in turn, is determined by Σ_ε (i.e., by the transparency regime). Note that as Σ_ε approaches infinity, $E[c_{i1}|P_1, N_1, P_2]$ approaches zero, because the information in N_1 approaches zero. In this limit, $P_2 = P_1 = 0$, and customers do not trade in period two (since P_2 is unbiased conditional on information available to them). Clearly, customers provide no risk sharing in this limit.

The following proposition provides an explicit value for c_{i2}. The proposition is conditional on a period-one trading rule, which we show below is consistent with the quoting rules from Propositions 1 and 2.

PROPOSITION 3. *If $T_{i1} = \phi c_{i1}$ for all $i \in \{1, \dots, n\}$, then P_2 is consistent with BNE only if for all $i \in \{1, \dots, n\}$,*

$$c_{i2} = \Lambda_N N_1 + \Lambda_P P_2,$$

where $\Lambda_N \equiv -[1 + (n/\theta\Sigma_2)]\Lambda_{cN}$, $\Lambda_P \equiv (1/\theta\Sigma_2)$, *and* $\Lambda_{cN} \equiv \phi\Sigma_c/(n\phi^2\Sigma_c + \Sigma_\varepsilon)$.

Proof. From Proposition 2, $c_{i2} = -E[D_{i2} + c_{i1}|P_1, N_1, P_2]$. Now, exponential utility and normality imply that $E[D_{i2}|P_1, N_1, P_2] = (1/\theta\Sigma_2)E[F|P_1, N_1, P_2] - (1/\theta\Sigma_2)P_2$. Further, since P_1 and P_2 provide no information beyond that in N_1, this last expression is equal to $(1/\theta\Sigma_2)E[F|N_1] - (1/\theta\Sigma_2)P_2 = (n/\theta\Sigma_2)E[c_{i1}|N_1] - (1/\theta\Sigma_2)P_2$. So we can write $c_{i2} = -[1 + (n/\theta\Sigma_2)]E[c_{i1}|N_1] - (1/\theta\Sigma_2)P_2$. Finally, it is straightforward to show that $E[c_{i1}|N_1] = [\phi\Sigma_c/(n\phi^2\Sigma_c + \Sigma_\varepsilon)]N_1 \equiv \Lambda_{cN}N_1$.

Note that the Σ_2 entering the expression for D_{i2} can be written as $\text{Var}[F - P_2|P_1, c_{i1}, T'_{i1}, N_1]$. This variance, however, does not depend on the realized values of the conditioning variables, and is therefore common knowledge at the outset.

The following proposition presents a BNE in linear strategies for each transparency regime, or Σ_ε.

PROPOSITION 4. *Given Σ_ε, the following quoting and trading rules define a BNE,*

$$P_{i1} = 0$$

$$T_{i1} = \phi c_{i1}$$

$$P_{i2} = \Lambda N_1$$

$$T_{i2} = \beta_1 c_{i1} + \beta_2 T'_{i1} + \beta_3 N_1,$$

where each holds for all $i \in \{1, \ldots, n\}$, and where Λ, β_1, β_2, and β_3 are defined below.

Proof. See Appendix A.

Discussion of the equilibrium may be helpful since our simultaneous trade model is less familiar than sequential trade and auction models. We touch on each of the four components of Proposition 4. First, that each dealer quotes $P_{i1} = 0$ in BNE is established in Proposition 1. Second, determining the trading rule for T_{i1} requires dynamic programming since dealers account for the impact of their period-one trades on P_2. Though the algebra involved is tedious, the resulting trading rule takes a simple form: each dealer's interdealer trade in period one is proportional to her customer order c_{i1}. This is not surprising given that dealer types are determined by c_{i1}, and P_{i1} provides no information regarding those types. The constant in the trading rule $T_{i1} = \phi c_{i1}$ is defined (implicitly) as

$$\phi \equiv 1 + \frac{\theta + (\Lambda - 1)(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2) + \gamma_3(\Lambda - 1)(\theta\Sigma_2 - \gamma_3)/\Sigma_2}{\Lambda(\theta\Sigma_2 - \gamma_3)^2/\Sigma_2 - 2\theta - \Lambda(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2)}.$$

Per Eq. (3), the first term reflects the one-for-one laying off of the customer order. The expected incoming dealer order equals zero since P_1 and c_{i1} provide no information about other dealers' customer orders (i.e., $E[T'_{i1} | \Omega_{Ti1}] = 0$). Thus, the second term reflects D_{i1}. From Eq. (A9) in the Appendix, there are three components to this speculative demand: the familiar component based on the revelation of F in P_2, and two strategic components arising from the impact of T_{i1} on P_2 (one capturing the effect on the period-one return, and one capturing the effect on the period-two return).

The third component of Proposition 4 is the quoting rule $P_{i2} = \Lambda N_1$. This is where the effects of the transparency regime are most apparent in that the information content in P_2 depends directly on the information in N_1. The equilibrium value of Λ (presented in the Appendix) is pinned down by the result that $c_{i2} = \Lambda_N N_1 + \Lambda_P P_2$ (Proposition 2) coupled with the relation $c_{i2} = \zeta(E[F | \Omega_{C2}] - P_2)$ from Eq. (2).

Finally, the period-two rule for T_{i2} is a straightforward substitution into Eq. (4). Its determination is straightforward because in period two the dealer faces a simple one-period problem. The coefficient values are presented in the Appendix.

The implications of this equilibrium are strong and merit some discussion. Specifically, order flow is the sole channel through which private information is revealed since using quotes to signal information is never optimal. This is a direct implication of avoiding arbitrage (which drives Propositions

1 and 2). We offer two arguments to support the equilibrium. First, the avoidance of arbitrage is a first-order concern for FX dealers. Quotes are good for substantially larger quantities than in other multiple-dealer markets: \$10 million in the DM/\$ market versus 1000 shares for NASDAQ. This coupled with effective spreads less than 0.02% (Lyons 1995) leaves little room for signaling with quotes without being arbitraged. A second disincentive to providing private information in quotes in this model is that it can increase the variance of the quoting dealer's position disturbance. This occurs because providing information in quotes reduces price risk faced by the dealer receiving the quote, which increases quantity demanded, ceteris paribus. The quantity demanded becomes the quoting dealer's position disturbance.

III. THE DEALER-OPTIMAL EQUILIBRIUM

This section has two parts. In the first, we determine the dealer-optimal BNE and characterize its properties. In the second part, we examine a benchmark example that clarifies the risk-sharing role of customers in period two.

A. *The Formal Solution*

Section I defines the dealer-optimal BNE as the BNE that results from the dealers' preferred transparency regime. The transparency regimes are indexed by Σ_ε (the variance of the noise in the volume signal N_1). Using the dealer's problem in Eq. (6), the dealer-optimal BNE corresponds to the solution to the problem

$$\begin{aligned} &\operatorname*{Max}_{\Sigma_\varepsilon} E[-\exp(-\theta W_{i2}) \mid \Omega_i] \\ &\text{s.t. } W_{i2} = (D_{i1} - T'_{i1})(P_2 - P_1) + (D_{i2} - T'_{i2})(F - P_2). \end{aligned} \tag{7}$$

Here, we suppress the terms relating to c_{i1}, c_{i2}, $E[T'_{i1} \mid \cdot]$, and $E[T'_{i2} \mid \cdot]$ since they equal zero in equilibrium. The terms arising from T'_{i1} and T'_{i2} account for the impact of position disturbances, a utility cost of market making. This utility cost is a function of the transparency regime since, per Section II, Σ_ε determines the risk sharing provided by customers in period two. This risk sharing by customers lowers the variance of the position disturbances dealers face in period two (a point clarified with the example below).

The first order condition of this problem, derived in Appendix B, is reproduced here. To ease notation, we define a variable for each of the four terms in final wealth from Eq. (7): $z_1 \equiv (D_{i1} - T'_{i1})$, $z_2 \equiv (D_{i2} - T'_{i2})$, $x_1 \equiv (P_2 - P_1)$, and $x_2 \equiv (F - P_2)$.

$$\left(\frac{d}{d\Sigma_\varepsilon}\right)(-|\Sigma_{W1}|^{-\frac{1}{2}}|A_1|^{-\frac{1}{2}} - |\Sigma_{W2}|^{-\frac{1}{2}}|A_2|^{-\frac{1}{2}}) = 0, \tag{8}$$

where

$$\Sigma_{Wt} \equiv \begin{bmatrix} \Sigma_{zt} & \rho_t \\ \rho_t & \Sigma_{xt} \end{bmatrix}$$

and

$$A_t \equiv \begin{bmatrix} (1/\Sigma_{zt})[1 + \rho_t^2/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2)] & -\rho_t/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) + \theta \\ -\rho_t/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) + \theta & \Sigma_{zt}/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) \end{bmatrix}.$$

Here, we use Σ_{zt} to denote the conditional variance of variable z in period t (similarly for the variable x), and ρ_t to denote the conditional covariance of the variables x and z in period t.

Though this solution is not enlightening by itself, the simulation results in Fig. 2 highlight an important point: When order flow is important for price formation (Σ_ν from Eq. (1) is low), dealers prefer less order-flow transparency. The figure shows the preferred transparency level Σ_ε as a function of Σ_ν, where ν is the component of F that is unrelated to order flow (we scale the values of Σ_ε and Σ_ν by the variance of the order-flow signal Σ_{N1} to ease interpretation). When Σ_ν is zero, dealers prefer that about half the variation in N_1 comes from noise (i.e., $\Sigma_\varepsilon/\Sigma_{N1} \approx 0.5$).

To see why dealers prefer greater transparency when Σ_ν is high, consider the limit as $\Sigma_\nu \to \infty$. In general, the more transparent the regime, the more precise $E[c_{i1}|N_1]$. The more precise $E[c_{i1}|N_1]$, the more risk sharing provided by customers in period two (Proposition 2). Since high Σ_ν implies a high return variance that necessarily occurs in period two, customer risk sharing is extremely valuable in this case. This period two benefit of greater transparency far outweighs the cost, which takes the form of greater return volatility in period one due to an N_1 that is more informative of $\Sigma_{i=1}^{n} c_{i1}$.

B. *Benchmark Example*

Here is a simple example to clarify further the risk-sharing role of customers in period two. The simplicity comes from two assumptions: (i) dealers face no adverse selection, and (ii) customer demand in period two is per-

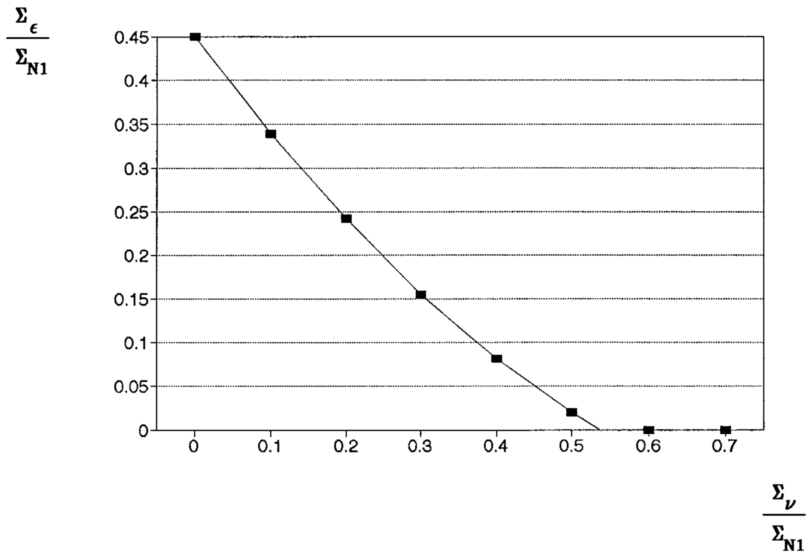


FIG. 2. Dealers' preferred transparency regime. The figure charts the ex ante preferred Σ_ε as a function of Σ_ν, where Σ_ε is the variance of the noise in order flow (Eq. (5)) and Σ_ν is the variance of the terminal value component that is independent of order flow (Eq. (1)). For this simulation the number of dealers n is set at 10, the coefficient of absolute risk aversion θ is set at 0.95, and customer demand in period two is perfectly elastic. To ease interpretation, the value of Σ_ε and Σ_ν are both scaled by the (endogenous) variance of the order-flow signal N_1; thus, the vertical axis provides a measure of the share of the signal's variance that the dealers would prefer is due to noise.

fectly elastic. (Abstracting from adverse selection has little effect in the end: Delaying revelation does not alter the original customer order that establishes information asymmetry at the outset. The second assumption is of no qualitative consequence, except when compared to the perfectly inelastic case.)

Under these assumptions the optimal transparency problem collapses to an intuitive form

$$\underset{\Sigma_\varepsilon}{\mathrm{Max}} - (1 - \theta^2\Sigma_{T1}\Sigma_1)^{-\frac{1}{2}} - (1 - \theta^2\Sigma_{T2}\Sigma_2)^{-\frac{1}{2}},$$

where Σ_{T1} and Σ_{T2} denote the conditional variance of the position disturbances T'_{i1} and T'_{i2}, and Σ_1 and Σ_2 denote the conditional return variances in periods one and two. To see the problem takes this form, note from the solution in Eq. (8) that the adverse selection problem is captured by the covariance terms ρ_t between $(D_{it} - T'_{it})$ and $(P_{t+1} - P_t)$, which are not equal to zero. It is straightforward to show that if $\rho_t = 0$ then speculative demand equals zero.

This expression clarifies the trade-off between first- and second-period revelation since it is qualitatively equivalent to minimizing

$$\Sigma_{T1}\Sigma_1 + \Sigma_{T2}\Sigma_2.$$

When Σ_ε is increased, less information is revealed in period-one trading, which pushes Σ_1 down and Σ_2 up. Whether dealers prefer this less transparent regime depends on the relative size of position disturbances in periods one and two. That is, the lower Σ_{T2} relative to Σ_{T1}, the greater the preference for second-period price discovery (i.e., higher Σ_2).

To see how customers lower Σ_{T2} relative to Σ_{T1}, consider the effect of Σ_ε on these variances. If dealers face no adverse selection, then from Eq. (4), we can express the position disturbance T'_{i2} as

$$T'_{i2} = c_{j2} + T'_{j1}$$

since $E[T'_{i1}|\Omega_{Ti1}] = 0$ in equilibrium, and D_{j2}, D_{j1}, and $E[T'_{j2}|\Omega_{Tj2}]$ all equal zero. (Here, dealer j is placing the order and T'_{j1} denotes the disturbance to dealer j's position in period one.) Appendix C shows that the conditional variance of $(c_{j2} + T'_{j1})$ together is less than the conditional variance of T'_{j1} alone. Economically, this reflects the customers' sharing of risk that would otherwise be borne by dealers: in period two customers absorb the estimated mean inventory imbalance from interdealer trading in period one (Proposition 3). Statistically, this reflects that c_{j2} is nonstochastic, and tends to be positive (customers buying in period two) when T'_{j1} is negative (dealer j was longer than desired in period one), and vice versa. Specifically,

$$\Sigma_{T2} = k\Sigma_{T1}, \tag{9}$$

where

$$k \equiv 1 - (2/n\phi). \tag{10}$$

This proportionality constant k is unambiguously less than 1 since $\phi \geq 1$.

To summarize, with no transparency customers do not trade in period two since they have no order-flow information. Since they do not trade, they cannot share the risk dealers face in period two. At the other extreme, if order flow is perfectly observable then the period-one return variance is at its maximum. Customer trading in period two does not alter the fact that dealers have already borne this price risk (from the position disturbance T'_{i1}).

The following three propositions provide comparative static results regarding the three core parameters of the model: (i) the number of dealers n, (ii) the coefficient of absolute risk aversion θ, and (iii) the variance of ν, the component of full-information value *not* impounded in order flow.

PROPOSITION 5. *The risk-sharing benefit of relaxing full transparency converges to* 0 *as the number of dealers approaches* ∞.

Proof. The risk-sharing benefit of $\Sigma_\varepsilon > 0$ derives from the fact that $k \equiv 1 - (2/n\phi) < 1$. Since $\phi \geq 1$, $k \to 1$ as $n \to \infty$.

PROPOSITION 6. *The risk-sharing benefit of relaxing full transparency converges to* 0 *as risk aversion approaches* 0.

Proof. $\phi \to \infty$ as $\theta \to 0$ since $D_{i1} \to \infty$. Since $k \equiv 1 - (2/n\phi)$, $k \to 1$ as $\phi \to \infty$.

PROPOSITION 7. *The risk-sharing benefit of relaxing full transparency converges to* 0 *as the correlation between order flow and full-information value approaches* 0.

Proof. All non-order-flow information, i.e., ν, is revealed after period-two trading. As $\Sigma_\nu/\Sigma_c \to \infty$, $\Sigma_1/\Sigma_2 \to 0$. In the limit dealers have no incentive to slow the revelation of $\sum_{i=1}^{n} c_{i1}$ in period one relative to the benefit that revelation provides from customer absorption of inventory imbalances in period two.

Another way to view Proposition 5 is that the source of the risk-sharing benefits—mean inventory imbalances—converges to 0 as $n \to \infty$. In Proposition 6, the mean inventory imbalance becomes painless as $\theta \to 0$.

IV. INSTITUTIONAL PERSPECTIVE ON THE MODEL

Some institutional background on the spot FX market helps motivate our modeling approach. The approach has three key dimensions and we provide background for each. The first key dimension is our specification of customer orders as the source of asymmetric information (see Eq. (1)). We provide evidence below that participants do indeed consider these orders privately informative and price relevant. The second key dimension is the simultaneous trade feature. This is the feature that generates dealer position disturbances. More familiar sequential trade and auction approaches preclude trade-induced position disturbances (via regret-free quoting or the ability to condition on market-clearing prices). Not only do position disturbances arise naturally in our model, they are crucial to the main result (that dealers might prefer slower price formation). Below we provide some evidence that position disturbances like those in the model are a common occurrence among dealers of FX. The third key dimension of our approach is the specification of order-flow transparency (see Eq. (5)). Below we address the insitutions that determine transparency in FX and the reasons order flow is observed with considerable noise.

Our specification of customer orders as a source of asymmetric information at the dealer level is based on the comments of dealers themselves. As described by Citibank's head of FX in Europe: ''If you don't have access to the end user, your view of the market will be severely limited'' (*Financial Times,* 4/29/91). In a similar spirit, Goodhart (1988) writes: ''A further source of informational advantage to the traders is their access to, and trained interpretation of, the information contained in the order flow ... Each bank will also know what its own customer enquiries and orders have been in the course of the day, and will try to deduce from that the positions of others in the market, and overall market developments as they unfold.'' These customer orders are not only informative, they are also privately observed: dealers have virtually no direct information about other banks' customer orders. These are the aspects of customer order flow that motivate the model's information structure.

The model's simultaneous trade feature—the second key dimension—produces trading patterns that accord well with stylized facts. In particular, the model produces hot potato trading, a term describing the repeated passing of inventory imbalances from dealer to dealer. There is compelling evidence that much of the enormous volume in FX comes from this type of trading. Indeed, Flood (1994) writes: ''The large volume of interbank trading is not primarily speculative in nature, but rather represents the tedious task of passing undesired positions along until they happen upon a marketmaker whose inventory discrepancy they neutralize.'' Undesired inventories are essential for capturing this hot potato process, and the simultaneous trade feature is our means of producing these disturbances.

The third key dimension of the model is that transparency is defined over order flow (See Eq. (5)). Empirically, order-flow transparency is much lower in FX than in equity markets. To see this, recall that customer–dealer trades (roughly 15% of volume) provide no transparency beyond the transacting parties. Of the remaining 85% of volume—all of which is interdealer—roughly two-thirds is done directly and a third is brokered. When dealers trade directly only the counterparties know the quantity; thus, like customer–dealer trades, direct interdealer trades provide no order-flow transparency. The only type of FX trade that provides marketwide signals of order flow is brokered interdealer trading.

Thus, order-flow transparency in FX is determined by the extent of brokered trading. Signals from brokered order flow arise as follows. Spot dealers trade while listening to intercoms linked to interdealer brokers who advertise firm prices (thereby providing marketwide price transparency).[6] When a transaction takes place that exhausts the quantity available at the advertised bid or offer, this fact is announced to the dealers. For example, if a broker is advertising a bid-offer of DM1.6045–DM1.6050 per dollar and a dealer buys the full quantity on offer, the broker will announce "50 paid," which indicates that a transaction exhausted the offer. Though the exact size is not known, this is still a signal since dealers have a sense of the typical size (Lyons (1995) reports a median brokered quantity of about $5 million). The exhausting of the bid or offer at a given broker accounts for about 50% of brokered transactions, depending on the currency (dealer estimates). This is the only order-flow signal available marketwide.

Is it the case that actual order-flow transparency is low because dealers prefer low transparency? Though our model does not address this directly (since it does not address *how* a transparency level is established), we offer some thoughts on the issue. First, recall that actual transparency has arisen without regulatory influence, so speaking of an endogenous level that serves dealers is a reasonable starting point. Clearly, though, the notion of a cooperative outcome does not square with the FX market's competitive decentralized structure. Cooperation is not necessary, however: private incentives might still produce an equilibrium share of brokered trading (i.e., transparent trading) that matches the actual share. As a supporting fact we note that transparency is similar across the world's trading centers: the share of total trading that is brokered ranges from 35 to 44% in the seven largest centers with comparable statistics (Bank for International Settlements (1990)). While it is true that dealers have other reasons for using brokers, brokered trading does determine transparency, so dealers are choosing the level of transparency de facto.

Because dealers have other reasons for using brokers we choose to isolate transparency rather than model brokers explicitly. (For example, brokered trading provides ex ante anonymity, whereas direct interdealer trading does not; more important, brokered trading introduces an element of execution risk not present in direct trading: providing a broker with a price does not ensure execution.) An interesting extension of our analysis would explicitly include the dealer's decision to trade in the transparent segment of the market (e.g., in the spirit of Admati and Pfleiderer (1991)). This would identify which types of trade are executed in the transparent segment and the attendant effects on information aggregation. Within this richer setting

[6] Over the past five years, voice-based brokerage has seen increasing competition from screen-based brokerage (e.g., the Reuters Dealing 2000-2 system). These screen-based systems provide order flow signals similar to those from traditional brokers. Recent direct dealing systems such as the screen-based Reuters Dealing 2000-1 provide the same transparency as traditional direct transactions, namely zero. For a study of other dimensions of electronic communication among FX dealers see Zaheer and Zaheer (1995).

one could determine the private trade-offs that lead to an equilibrium aggregate transparency (i.e., an equilibrium share of brokered trading).[7] Perhaps more interesting, one could address any distortionary effects from the fact that transparency here emerges as a by-product of brokered trading—an activity that jointly serves many purposes.

V. CONCLUSIONS

The key to optimal transparency here is that order-flow information plays two roles. The first is in allocating price formation between the two periods. The second is in providing customers with information for their trades in period two. From the dealer perspective, the trade-off is the following. If there is no transparency, customers will not trade in period two, and therefore cannot share risk otherwise borne by dealers. At the other extreme, full transparency ensures that the interim price reveals all order-flow information. In this case all price risk has been absorbed by dealers already, so customer risk-sharing in period two is moot (to be precise, all price risk has been absorbed only in the case where $\Sigma_\nu = 0$). The optimal regime trades off the benefit of customer participation in period two against the cost of added return variance in period one from inducing that participation (via added order-flow information).

To our knowledge, this paper is the first to address the microstructural trade-off between the pace of price formation and the amount of risk sharing. From a market-design perspective, the approach formalizes the notion of optimal noise (in this case, from the dealer perspective). It is tempting to argue that the current transparency regime in FX, having endogenously emerged without publication requirements, might be optimal from the dealer perspective without being optimal at a broader level. Making the case compelling, however, requires a richer model than that developed here.

Transparency has many dimensions: pre-trade versus post-trade information, quantity versus price information, dealer versus public information, and many others. This papers focuses on the transparency of post-trade quantity information. In contrast, the existing literature (see Introduction) focuses mainly on pre-trade quantity information. In our judgment, it is post-trade quantity information that is central to the current policy debate. This is an important reason we adopt the approach we do. At a more specific level, we model transparency regimes as determining the precision of trade publication, rather than, say, the speed of publication. Empirically,

[7] For example, one could determine whether brokerage services offering a transparency level that differs from that of existing brokers would have incentives to enter.

some trade information is typically available immediately and some becomes available with a delay. Indexing regimes with precision is at least consistent with this. Institutionally, modeling the speed of publication explicitly would require multiple distinct speeds. We consider this an interesting avenue for future research.

APPENDIX

A. *Determining Linear Bayesian–Nash Equilibrium*

Determining the dynamic programming solution conditional on a given transparency regime (or Σ_ε) requires the period-two desired position for use in the period-one first order condition. Under normality and exponential utility it is well known that the period-two desired position is

$$D_{i2} = (\gamma_{iF} - P_2)(\theta\Sigma_2)^{-1}, \tag{A1}$$

where $\gamma_{iF} \equiv E[F \,|\, P_1, c_{i1}, T'_{i1}, N_1]$ and $\Sigma_2 \equiv \mathrm{Var}[F - P_2 \,|\, P_1, c_{i1}, T'_{i1}, N_1]$. Hence, omitting terms unrelated to D_{i1} one can write the dealers' problem as

$$\begin{aligned}\operatorname*{Max}_{D_{i1}} E_{P_2,\gamma_{iF},F}[&-\exp(-\theta D_{i1}(P_2 - P_1)\\ &- (\gamma_{iF} - P_2)(\Sigma_2)^{-1}(F - P_2)) \,|\, P_1, c_{i1}].\end{aligned} \tag{A2}$$

From the law of iterated projections the expectation can be written as

$$\begin{aligned}E_{P_2,\gamma_{iF}}[E_F[&-\exp(-\theta D_{i1}(P_2 - P_1)\\ &- (\gamma_{iF} - P_2)(\Sigma_2)^{-1}(F - P_2)) \,|\, P_1, c_{i1}, T'_{i1}, N_1] \,|\, P_1, c_{i1}].\end{aligned}$$

Making use of the definition of the moment generating function for a random variable $x \sim N(\mu, \sigma^2)$: $E[\exp(tx)] = \exp(\mu t + \sigma^2 t^2/2)$, the inside expectation over F yields

$$E_F[\,\cdot\,| P_1, c_{i1}, T'_{i1}, N_1] = -\exp(-\theta D_{i1}(P_2 - P_1) - (2\Sigma_2)^{-1}(\gamma_{iF} - P_2)^2) \tag{A3}$$

since $E[F - P_2 \,|\, P_1, c_{i1}, T'_{i1}, N_1] = \gamma_{iF} - P_2$ and

$$\begin{aligned}&-\exp((\gamma_{iF} - P_2)(-1)(\gamma_{iF} - P_2)(\Sigma_2)^{-1} + (1/2)\Sigma_2[-(\gamma_{iF} - P_2)(\Sigma_2)^{-1}]^2)\\ &\quad = -\exp(-(\gamma_{iF} - P_2)^2(\Sigma_2)^{-1} + (1/2)[(\gamma_{iF} - P_2)^2(\Sigma_2)^{-1}])\\ &\quad = -\exp(-(2\Sigma_2)^{-1}(\gamma_{iF} - P_2)^2).\end{aligned}$$

This simplifies the objective function to

$$\operatorname*{Max}_{D_{i1}} E_{P_2,\gamma_{iF}}[-\exp(-\theta D_{i1}(P_2 - P_1) - (2\Sigma_2)^{-1}(\gamma_{iF} - P_2)^2) \,|\, P_1, c_{i1}]. \quad \text{(A4)}$$

Now we introduce an expression for the period-two price. From Proposition 4, the common period-two quote takes the form

$$P_2 = \Lambda N_1, \quad \text{(A5)}$$

where $\Lambda \equiv (\Lambda_p + \zeta)^{-1}[\zeta n\Lambda_{cN} - \Lambda_N]$. To see this, recall from Proposition 3 that $c_{i2} = \Lambda_N N_1 + \Lambda_P P_2$, and from Eq. (2), we know that $c_{i2} = \zeta(E[F\,|\,\Omega_{C2}] - P_2)$. These two equations pin down P_2: $\Lambda_N N_1 + \Lambda_P P_2 = \zeta E[F\,|\,\Omega_{C2}] - \zeta P_2 \Rightarrow P_2 = (\Lambda_P + \zeta)^{-1}[\zeta n E[c_{i1}\,|\,\Omega_{C2}] - \Lambda_N N_1] = (\Lambda_P + \zeta)^{-1}[\zeta n\Lambda_{cN} - \Lambda_N]N_1$, where Λ_{cN} extracts c_{i1} from N_1 (defined in Proposition 3). The derivation of the trading rule below is based on this quoting rule which ensures their consistency.

In order to determine $\gamma_{iF} - P_2$, define the signal extraction coefficient λ_{cN}, which extracts $\sum_{k\neq i,j}^{n} c_{k1}$ from the statistic $(N_1 - T_{i1} - T'_{i1})$, as

$$\lambda_{cN} \equiv \phi\Sigma_c/[\Sigma_T + \Sigma_\varepsilon/(n-2)],$$

where ϕ and Σ_T are determined from the optimal period-one trading rule (Proposition 4). One can then write

$$\begin{aligned}
\gamma_{iF} - P_2 &= E[F - \Lambda N_1 \,|\, P_1, c_{i1}, T'_{i1}, N_1] \\
&= E\left[\sum_{i=1}^{n} c_{i1} - \Lambda N_1 \,\middle|\, P_1, c_{i1}, T'_{i1}, N_1\right] \\
&= E\left[c_{i1} + c_{j1} + \sum_{k\neq i,j}^{n} c_{k1} - \Lambda N_1 \,\middle|\, P_1, c_{i1}, T'_{i1}, N_1\right] \qquad \text{(A6)} \\
&= c_{i1} + (1/\phi)T'_{i1} + \lambda_{cN}(N_1 - T_{i1} - T'_{i1}) - \Lambda N_1 \\
&= c_{i1} - \lambda_{cN}T_{i1} + (1/\phi - \lambda_{cN})T'_{i1} + (\lambda_{cN} - \Lambda)N_1,
\end{aligned}$$

where c_{j1} is the customer order embedded in T'_{i1}, and the best estimate of c_{j1} conditional on T'_{i1} is $(1/\phi)T'_{i1}$ since $T'_{i1} = \phi c_{j1}$. This is an important expression: it summarizes dealer i's beliefs about the period-two return as a function of four variables observable by him. The problem in Eq. (A4) can thus be written as

$$\underset{D_{i1}}{\text{Max}}\, E_{P_2,T'_{i1}}[-\exp(-\theta D_{i1}(P_2 - P_1)$$
$$-(2\Sigma_2)^{-1}[c_{i1} - \lambda_{cN} T_{i1} + (1/\phi - \lambda_{cN})T'_{i1} + (\lambda_{cN} - \Lambda)N_1]^2)\,|\,P_1, c_{i1}]. \quad \text{(A7)}$$

Since dealer i considers the effect of her demand on the period-two price, it would not be appropriate to take the expectation over the random variable P_2. It is necessary to define a new variable, N'_1:

$$N'_1 \equiv N_1 - T_{i1}. \quad \text{(A8)}$$

Since $P_2 = \Lambda N_1 = \Lambda(D_{i1} + c_{i1} + N'_1)$ and $P_1 = 0$ the objective function becomes

$$\underset{D_{i1}}{\text{Max}}\, E_{N'_1,T'_{i1}}[-\exp[-\theta\Lambda D_{i1}\,(D_{i1} + c_{i1} + N'_1)$$
$$-(2\Sigma_2)^{-1}[(1-\Lambda)c_{i1} - \Lambda D_{i1} + (1/\phi - \lambda_{cN})T'_{i1} + (\lambda_{cN} - \Lambda)N'_1]^2]\,|\,c_{i1}]. \quad \text{(A9)}$$

The next step is integrating over the random variable T'_{i1}. Recognizing that

$$E[T'_{i1}\,|\,c_{i1}] = 0$$

and

$$\text{Var}[T'_{i1}\,|\,c_{i1}] = \phi^2\Sigma_c \equiv \Sigma_T,$$

where ϕ is from the linear trading rule in Proposition 4, one can write an objective function proportional to that in Eq. (A9):

$$\underset{D_{i1}}{\text{Max}}\, E_{N'_1}\int_{-\infty}^{\infty} - \exp[-\theta\Lambda D_{i1}(D_{i1} + c_i + N'_1)$$
$$- (2\Sigma_2)^{-1}[(1-\Lambda)c_{i1} - \Lambda D_{i1} + (1/\phi - \lambda_{cN})T'_{i1} \quad \text{(A10)}$$
$$+ (\lambda_{cN} - \Lambda)N'_1]^2 - (1/2)(\Sigma_T)^{-1}(T'_{i1})^2\,|\,c_{i1}]\, dT'_{i1}.$$

Collecting terms involving T'_{i1}, omitting terms unrelated to D_{i1}, and introducing a notation-simplifying constant $\gamma_1 \equiv (1/\phi - \lambda_{cN})$ yields

$$\begin{aligned}\underset{D_{i1}}{\text{Max}}\, E_{N'_1}\int_{-\infty}^{\infty} &- \exp[-\theta\Lambda D_{i1}(D_{i1} + c_i + N'_1) - (2\Sigma_2)^{-1}[(1-\Lambda)c_{i1} - \Lambda D_{i1} \\ &+ (\lambda_{cN} - \Lambda)N'_1]^2 - (2\Sigma_2)^{-1}[2\gamma_1((1-\Lambda)c_{i1} \\ &- \Lambda D_{i1})T'_{i1} + \gamma_1^2(T'_{i1})^2] - (1/2)(\Sigma_T)^{-1}(T'_{i1})^2 \,|\, c_{i1}]\, dT'_{i1}.\end{aligned}$$

Factoring the quadratic terms in T'_{i1} yields

$$\begin{aligned}\underset{D_{i1}}{\text{Max}}\, E_{N'_1}\int_{-\infty}^{\infty} &- \exp[-\theta\Lambda D_{i1}(D_{i1} + c_i + N'_1) - (2\Sigma_2)^{-1}[(1-\Lambda)c_{i1} - \Lambda D_{i1} \\ &+ (\lambda_{cN} - \Lambda)N'_1]^2 + (2\gamma_2)^{-1}(\gamma_1/\Sigma_2)^2[(1-\Lambda)c_{i1} - \Lambda D_{i1}]^2 \\ &- \tfrac{1}{2}\gamma_2(T'_{i1} + (\gamma_1/\gamma_2\Sigma_2)[(1-\Lambda)c_{i1} - \Lambda D_{i1}])^2 \,|\, c_{i1}]\, dT'_{i1},\end{aligned}$$

where we have introduced the notation-simplifying constant $\gamma_2 \equiv \gamma_1^2\Sigma_2^{-1} + \Sigma_T^{-1}$. The objective function can now be expressed as

$$\begin{aligned}\underset{D_{i1}}{\text{Max}}\, E_{N'_1}[&-\exp[-\theta\Lambda D_{i1}(D_{i1} + c_i + N'_1) - (2\Sigma_2)^{-1}[(1-\Lambda)c_{i1} - \Lambda D_{i1} \\ &+ (\lambda_{cN} - \Lambda)N'_1]^2 + (2\gamma_2)^{-1}(\gamma_1/\Sigma_2)^2[(1-\Lambda)c_{i1} - \Lambda D_{i1}]^2 \\ &\times \int_{-\infty}^{\infty} \exp(-\tfrac{1}{2}\gamma_2(T'_{i1} + (\gamma_1/\gamma_2\Sigma_2)[(1-\Lambda)c_{i1} - \Lambda D_{i1}])^2) \,|\, c_{i1}]\, dN'_1.\end{aligned}$$

Recognizing that the integral in the last term is proportional to a cumulative normal density with a mean of $-(\gamma_1/\gamma_2\Sigma_2)[(1 - \Lambda)c_{i1} - \Lambda D_{i1})]$ and a variance of $1/\gamma_2$, maximizing this whole expression is equivalent to maximizing

$$\begin{aligned}\underset{D_{i1}}{\text{Max}}\, E_{N'_1}[&-\exp[-\theta\Lambda D_{i1}(D_{i1} + c_i + N'_1) - (2\Sigma_2)^{-1}[(1-\Lambda)c_{i1} - \Lambda D_{i1} \\ &+ (\lambda_{cN} - \Lambda)N'_1]^2 + (2\gamma_2)^{-1}(\gamma_1/\Sigma_2)^2[(1-\Lambda)c_{i1} - \Lambda D_{i1}]^2 \,|\, c_{i1}]. \qquad \text{(A11)}\end{aligned}$$

Solving this problem follows the same steps used in integrating over the random variable T'_{i1} above. Note that

$$E[N'_1 \,|\, c_{i1}] = 0 \qquad \text{and} \qquad \text{Var}[N'_1 \,|\, c_{i1}] = (n-1)\Sigma_T + \Sigma_\varepsilon \equiv \Sigma_{N'}.$$

One can thus write an objective function proportional to that in Eq. (A11):

$$\begin{aligned}\underset{D_{i1}}{\mathrm{Max}} - \int_{-\infty}^{\infty} \exp[-\theta\Lambda D_{i1}(D_{i1} + c_{\mathrm{i}} + N_1') - (2\Sigma_2)^{-1}[(1-\Lambda)c_{i1} - \Lambda D_{i1} \\ + (\lambda_{cN} - \Lambda)N_1']^2 + (2\gamma_2)^{-1}(\gamma_1/\Sigma_2)^2[(1-\Lambda)c_{i1} - \Lambda D_{i1}]^2 \qquad \text{(A12)} \\ - (1/2)(\Sigma_{N'})^{-1}(N_1')^2]\, dN_1'.\end{aligned}$$

Collecting N_1' terms and introducing a constant $\gamma_3 \equiv (\lambda_{cN} - \Lambda)$ yields

$$\begin{aligned}= \underset{D_{i1}}{\mathrm{Max}} - \int_{-\infty}^{\infty} \exp[-\tfrac{1}{2}(2\theta\Lambda D_{i1}^2 + 2\theta\Lambda c_{i1}D_{i1} \\ + (1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2)[(1-\Lambda)c_{i1} - \Lambda D_{i1}]^2 \\ + [2(1/\Sigma_2)(1-\Lambda)\gamma_3 c_{i1} - 2(1/\Sigma_2)\Lambda\gamma_3 D_{i1} + 2\theta\Lambda D_{i1}]N_1' \\ + [(\gamma_3^2/\Sigma_2) + (1/\Sigma_{N'})]N_1'^2)]\, dN_1'.\end{aligned}$$

Factoring the terms in N_1' and introducing a constant $\gamma_4 \equiv (\gamma_3^2/\Sigma_2 + 1/\Sigma_{N'})$ yields

$$\begin{aligned}= \underset{D_{i1}}{\mathrm{Max}} - \int_{-\infty}^{\infty} \exp[-\tfrac{1}{2}(2\theta\Lambda D_{i1}^2 + 2\theta\Lambda c_{i1}D_{i1} \\ + (1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2)[(1-\Lambda)c_{i1} - \Lambda D_{i1}]^2 \\ - \gamma_4([(1-\Lambda)\gamma_3 c_{i1} + (\theta\Lambda\Sigma_2 - \Lambda\gamma_3)D_{i1}]/\gamma_4\Sigma_2)^2) \\ - \tfrac{1}{2}\gamma_4(N_1' + [(1-\Lambda)\gamma_3 c_{i1} + (\theta\Lambda\Sigma_2 - \Lambda\gamma_3)D_{i1}]/\gamma_4\Sigma_2)^2\, dN_1'.\end{aligned}$$

As above, the integral corresponding to the last term is proportional to a cumulative normal density. In this case the mean equals $-[(1-\Lambda)\gamma_3 c_{i1} + (\theta\Lambda\Sigma_2 - \Lambda\gamma_3)D_{i1}]/\gamma_4\Sigma_2$ and the variance equals $1/\gamma_4$. Maximizing this whole expression is equivalent to maximizing the expression in large curved brackets:

$$\begin{aligned}\underset{D_{i1}}{\mathrm{Max}}\, (2\theta\Lambda D_{i1}^2 + 2\theta\Lambda c_{i1}D_{i1} + (1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2)[(1-\Lambda)c_{i1} - \Lambda D_{i1}]^2 \\ - \gamma_4([(1-\Lambda)\gamma_3 c_{i1} + (\theta\Lambda\Sigma_2 - \Lambda\gamma_3)D_{i1}]/\gamma_4\Sigma_2)^2). \quad \text{(A13)}\end{aligned}$$

The first order condition yields

$$\begin{aligned}(4\theta\Lambda + 2\Lambda^2(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2) - 2(\theta\Lambda\Sigma_2 - \Lambda\gamma_3)^2/\Sigma_2)D_{i1} \\ + (2\theta\Lambda - 2\Lambda(1-\Lambda)(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2) \\ - 2\gamma_3(1-\Lambda)(\theta\Lambda\Sigma_2 - \Lambda\gamma_3)/\Sigma_2)c_{i1} = 0\end{aligned}$$

or

$$D_{i1} = \left(\frac{\theta + (\Lambda - 1)(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2) + \gamma_3(\Lambda - 1)(\theta\Sigma_2 - \gamma_3)/\Sigma_2}{\Lambda(\theta\Sigma_2 - \gamma_3)^2/\Sigma_2 - 2\theta - \Lambda(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2)} \right) c_{i1}.$$

From Eq. (3), $T_{i1} = D_{i1} + c_{i1} + E[T'_{i1} | \Omega_{Ti1}]$. But, $E[T'_{i1} | \Omega_{Ti1}] = 0$, so we can write

$$T_{i1} = \left(1 + \frac{\theta + (\Lambda - 1)(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2) + \gamma_3(\Lambda - 1)(\theta\Sigma_2 - \gamma_3)/\Sigma_2}{\Lambda(\theta\Sigma_2 - \gamma_3)^2/\Sigma_2 - 2\theta - \Lambda(1/\Sigma_2 - \gamma_1^2/\Sigma_2^2\gamma_2)} \right) c_{i1}$$
$$= \phi c_{i1}.$$

The period two trading rule is determined by substituting into Eq. (4).

$$T_{i2} = D_{i2} + c_{i2} - D_{i1} + (T'_{i1} - E[T'_{i1} | \Omega_{Ti1}]) + E[T'_{i2} | \Omega_{Ti2}] \qquad (4)$$

Since $D_{i2} = (\gamma_{iF} - P_2)/\theta\Sigma_2$, we can use the expression in Eq. (A6) for $(\gamma_{iF} - P_2)$, and the expression for c_{i2} from Proposition 3 to write

$$T_{i2} = \left(\frac{1 - \lambda_{cN}\phi}{\theta\Sigma_2} - (\phi - 1) \right) c_{i1} + \left(1 + \frac{2/\phi - \lambda_{cN}}{\theta\Sigma_2} \right) T_{i1}$$
$$+ \left(\frac{\lambda_{cN} - \Lambda_{cN} - \Lambda}{\theta\Sigma_2} + \Lambda_N + \Lambda_P\Lambda \right) N_1 \equiv \beta_1 c_{i1} + \beta_2 T'_{i1} + \beta_3 N_1.$$

B. *Determining the Dealer-Optimal Bayesian–Nash Equilibrium*

Determining the dealers' preferred transparency regime involves products of normally distributed random variables (see for example Bray, 1981). The problem is expressed in the text as

$$\operatorname*{Max}_{\Sigma_\varepsilon} E[-\exp(-\theta W_{i2}) | \Omega_i]$$

$$\text{s.t. } W_{i2} = (D_{i1} - T'_{i1})(P_2 - P_1) + (D_{i2} - T'_{i2})(F - P_2).$$

We begin by simplying notation. Let $z_1 \equiv (D_{i1} - T'_{i1})$, $z_2 \equiv (D_{i2} - T'_{i2})$,

$x_1 \equiv (P_2 - P_1)$, and $x_2 \equiv (F - P_2)$, where each has an unconditional mean of zero. The problem can be expressed as

$$\underset{\Sigma_\varepsilon}{\text{Max}} - |\Sigma_{W1}|^{-\frac{1}{2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp(-W_1)\, dz_1\, dx_1$$
$$- |\Sigma_{W2}|^{-\frac{1}{2}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp(-W_2)\, dz_2\, dx_2,$$

were

$$W_t \equiv \theta z_t x_t + \tfrac{1}{2}(z_t, x_t)\Sigma_{Wt}^{-1}(z_t, x_t)'$$

and

$$\Sigma_{Wt} \equiv \begin{bmatrix} \Sigma_{zt} & \rho_t \\ \rho_t & \Sigma_{xt} \end{bmatrix},$$

for $t = 1, 2$. Here, ρ_t denotes the conditional covariance of the variables x and z in period t. The first term in each of the W's is from the utility function, the second from the normal density function. Rational expectations ensures orthogonality of the W's. Since

$$\Sigma_{Wt}^{-1} = \begin{bmatrix} (1/\Sigma_{zt})[1 + \rho_t^2/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2)] & -\rho_t/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) \\ -\rho_t/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) & \Sigma_{zt}/\Sigma_{zt}\Sigma_{xt} - \rho_t^2) \end{bmatrix},$$

by rearranging we can write

$$W_t \equiv \tfrac{1}{2} y_t' A_t y_t,$$

where

$$y_t = (z_t, x_t)'$$
$$A_t = \begin{bmatrix} (1/\Sigma_{zt})[1 + \rho_t^2/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2)] & -\rho_t/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) + \theta \\ -\rho_t/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) + \theta & \Sigma_{zt}/(\Sigma_{zt}\Sigma_{xt} - \rho_t^2) \end{bmatrix}.$$

With the assumption that both of the A_t are positive definite we can write

$$A_t = D_t D_t'.$$

Using the substitution $u_t \equiv D_t' y_t$ we have

$$\begin{aligned}
&\operatorname*{Max}_{\Sigma_\varepsilon} -|\Sigma_{W1}|^{-\frac{1}{2}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \exp(-W_1)\, dz_1\, dx_1 \\
&\quad - |\Sigma_{W2}|^{-\frac{1}{2}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \exp(-W_2)\, dz_2\, dx_2 \\
&= \operatorname*{Max}_{\Sigma_\varepsilon} -|\Sigma_{W1}|^{-\frac{1}{2}} \int_{\mathbb{R}^2} \exp(-\tfrac{1}{2} y_1' A_1 y_1)\, dy_1 \\
&\quad - |\Sigma_{W2}|^{-\frac{1}{2}} \int_{\mathbb{R}^2} \exp(-\tfrac{1}{2} y_2' A_2 y_2)\, dy_2 \\
&= \operatorname*{Max}_{\Sigma_\varepsilon} -|\Sigma_{W1}|^{-\frac{1}{2}} |A_1|^{-\frac{1}{2}} \int_{\mathbb{R}^2} \exp(-\tfrac{1}{2} u_1' u_1)\, du_1 \\
&\quad - |\Sigma_{W2}|^{-\frac{1}{2}} |A_2|^{-\frac{1}{2}} \int_{\mathbb{R}^2} \exp(-\tfrac{1}{2} u_2' u_2)\, du_2,
\end{aligned}$$

where the $|A_t|^{-\frac{1}{2}}$ terms account for the rescaling of the multinormal variance required by the substitution. The problem can then be expressed as

$$\operatorname*{Max}_{\Sigma_\varepsilon} -|\Sigma_{W1}|^{-\frac{1}{2}} |A_1|^{-\frac{1}{2}} - |\Sigma_{W2}|^{-\frac{1}{2}} |A_2|^{-\frac{1}{2}}$$

since $\int_{\mathbb{R}^2} \exp(-\frac{1}{2} u_t' u_t)\, du_t$ is proportional to a cumulative multinormal density with means zero and variance–covariance I. The first order condition generates the ex ante preferred Σ_ε:

$$\left(\frac{d}{d\Sigma_\varepsilon}\right)\left(-|\Sigma_{W1}|^{-\frac{1}{2}} |A_1|^{-\frac{1}{2}} - |\Sigma_{W2}|^{-\frac{1}{2}} |A_2|^{-\frac{1}{2}}\right) = 0. \tag{8}$$

C. *The Benchmark Example*

We begin with an expression for the position disturbance T_{i2}' from Eq. (4),

$$T_{i2}' = D_{j2} - D_{j1} + c_{j2} + T_{j1}' + E[T_{j2}' \,|\, \Omega_{Tj2}],$$

where we suppress the $E[T_{j1}' \,|\, \Omega_{Tj1}]$ term since it equals zero in equilibrium. Now, since by assumption in this example dealers face no adverse selection problem, D_{j2}, D_{j1}, and $E[T'_{j2} | \Omega_{Tj2}]$ are zero. Further, at $\Sigma_\varepsilon = 0$, $\Lambda_{cN} = 1/n\phi$, which implies

$$c_{j2} = -\Lambda_{cN} N_1 = -(1/n\phi) \sum_i T'_{i1}.$$

Using this expression, we can write

$$\begin{aligned}
\Sigma_{T2} &= \mathrm{Var}\left[T'_{j1} - (1/n\phi) \sum_i T'_{i1} \,\middle|\, \Omega_{Ti2} \right] \\
&= \Sigma_{T1} + \mathrm{Var}\left[(1/n\phi) \sum_i T'_{i1} \,\middle|\, \Omega_{Ti2} \right] \\
&\quad + 2\,\mathrm{Cov}\left[T'_{j1}, -(1/n\phi) \sum_i T'_{i1} \,\middle|\, \Omega_{Ti2} \right].
\end{aligned}$$

Recalling that $N_1 = \sum_i T'_{i1}$ is contained in Ω_{Ti2}, the second variance term is zero, which implies

$$\begin{aligned}
\Sigma_{T2} &= \Sigma_{T1} - 2(1/n\phi)\Sigma_{T1} \\
&= (1 - (2/n\phi))\Sigma_{T1}
\end{aligned}$$

which is Eq. (9) in the text.

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