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Liquidity supply and adverse selection in a pure limit order book market

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Abstract

Based on a structural model we analyze adverse selection costs and liquidity supply in a pure open limit order book market. Given the discontenting empirical model performance reported in the previous literature, we relax restrictive assumptions of the underlying theoretical model concerning order book equilibrium and the distribution of market order volumes. We demonstrate that the resulting revised econometric methodology delivers considerably improved empirical results. Employing the alternative approach in a cross sectional analysis we provide evidence that adverse selection costs are more severe for smaller capitalized stocks, and find empirical support for one of the main hypothesis put forth by the theory of limit order book markets, which states that liquidity supply and adverse selection costs are inversely related. We also show that adverse selection component estimates based on the formal model and those obtained using popular model-free methods are closely correlated. This result indicates the robustness of the structural model, but also provides a theoretical underpinning for the application of the ad hoc method to limit order book data.

Keywords: Limit order book market, liquidity supply, adverse selection

JEL classification: G10, C32

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1 Introduction

Ten years after, the question phrased in Glosten's (1994) celebrated paper: 'Is the electronic order book inevitable?' seems to be answered, given the triumphal procession of open order book systems in Continental Europe and recent developments in US stock markets.[1] A central feature of a pure limit order book market is the absence of dedicated market makers. Liquidity is supplied voluntarily by patient market participants who provide an inflow of limit buy and sell orders, the lifeblood of the trading process. The non-executed orders constitute the limit order book, the consolidated source of liquidity. As the viability and resiliency of such a market structure is in the interest of regulators, operators and individual investors it is not surprising that theoretical and empirical studies of limit order markets abound in the literature.[2] However, theoretical models explaining liquidity supply and demand in limit order book markets have not been very successful when confronted with real world order book data. Sandas (2001) extends the methodology proposed by De Jong et al. (1996) and estimates a version of Glosten's (1994) limit order book model allowing for real world features like discrete price ticks and time priority rules. The empirical results obtained using data from the Swedish stock exchange were not encouraging. Formal specification tests reject the model, transaction costs estimates are significantly negative, and book depth is systematically overestimated.

This paper shows how some restrictive assumptions of Glosten/Sandas type models concerning order book equilibrium and the distribution of market order sizes can be relaxed, while retaining suitable moment conditions for GMM estimation. We show that the resulting revised econometric methodology considerably improves the empirical performance. The alternative approach is employed in a cross sectional analysis of adverse selection costs and liquidity supply in a limit order market.

Given the discontenting results reported in the previous literature, it is not surprising that many recent empirical papers analyzing limit order book market data have severed the close

[1]In January 2002 the New York Stock Exchange (NYSE), known as a hybrid specialist market, adopted the key feature of electronic order book markets, namely the public display of all limit orders (NYSE open book program).

[2]Traditionally, market microstructure theory focussed on quote driven markets with one or more market makers (see O'Hara (1995) for an overview). Recent papers by Parlour (1998), Seppi (1997) Foucault (1999) and Foucault et al. (2003) have changed the focus to the analysis of price and liquidity processes in order book markets.

connection to the theoretical framework. Extending the approach of the early paper by Biais et al. (1995), Hall et al. (2003), Coppejans et al. (2003), Cao et al. (2004), Grammig et al. (2004), Pascual and Veredas (2004) and Ranaldo (2004) employ discrete choice and count data models to analyze the determinants of order submission activity and the interaction of liquidity supply and demand processes in limit order markets. Beltran et al. (2004) advocate a principal components aproach to extract latent factors that explain the state of the order book. Gomber et al. (2004) and Degryse et al. (2003) conduct intra-day event studies to analyze the resiliency of limit order markets. These papers interpret the empirical results in the light of predictions of microstructure models. However, a structural interpretation of the parameter estimates cannot be delivered.

This paper returns to the theoretical basis for the empirical analysis of limit order book markets. We hypothesize that the discontenting empirical model performance is due to the following problems. First, the real world trading process might be organized in a way that deviates too much form the theoretical framework. Second, some of the underlying theoretical model's assumptions might be too restrictive. The Glosten (1994) model imposes a zero expected profit condition for order book equilibrium which may not hold in a very active order market with discrete price ticks and time priority rules. Furthermore, the parametric distribution of market order sizes assumed by Sandas (2001), though leading to convenient closed form liquidity supply equations and GMM moment conditions, might be misspecified. Hasbrouck (2004) conjectures that the latter is responsible for the empirical failure of the model.

The original methodological contribution of this paper is to propose an alternative approach which relaxes these restrictive assumptions while still delivering convenient moment conditions that can be employed for GMM estimation and testing. For this purpose, we replace the zero expected marginal profit conditions by more robust conditions for order book equilibrium which are based on less restrictive assumptions regarding limit order trader behavior. Furthermore, we show that the parametric distributional assumption about market order sizes can be abandoned in favor of a straightforward nonparametric alternative.

We estimate the model using both the standard and the revised methodology based on reconstructed order book data from the Xetra electronic order book system which operates at various European exchanges. The data are tailor-made for the purpose of this paper since the trading protocol closely corresponds to the theoretical trading process from which the moment conditions used for the empirical methodology are derived. We show that the revised econometric methodology delivers a much better empirical performance. Encouraged by the results, we employ the model in a cross sectional analysis of adverse selection effects and liquidity in the Xetra limit order market. This is the original empirical contribution of the paper. We report the following main results. First, we provide new evidence, from a limit order market, that adverse selection effects are more severe for smaller capitalized, less frequently traded stocks. This corroborates the results of previous papers dealing with different theoretical backgrounds, empirical methodologies, and market structures. Second, the empirical results support one of the main hypothesis of the theory of limit order markets, namely that book liquidity and adverse selection effects are inversely related. Finally, we compare the adverse selection components implied by the structural model estimates with poplar ad hoc measures which are based on a comparison of effective and realized spreads. The latter approach is model-free, frequently used in practice and academia (see e.g. Boehmer (2004) and SEC (2001)) and requires publicly available trade and quote data only. The first approach is based on an structural model, permits an economic interpretation of the structural parameters, but the demand on the data is higher, as reconstructed order books are needed. We show that both methodologies lead to quite similar conclusions. This result indicates the robustness of the structural model approach. It also provides a theoretical underpinning for using the ad-hoc method for the analysis of limit order data.

The remainder of the paper is organized as follows. Section 2 describes the market structure and the data. Section 3 discusses the theoretical background and develops the empirical methodology. The empirical results are discussed in section 4. Section 5 concludes with a summary and an outlook for further research.

2 Market structure and data

2.1 The Xetra open limit order book system

In our empirical analysis we use data from the automated auction system Xetra which is employed at various European trading venues, like the Vienna Stock Exchange, the Irish Stock Exchange, the Frankfurt Stock Exchange (FSE) and the European Energy Exchange.

Xetra is a pure open order book system developed and maintained by the German Stock Exchange. It has operated since 1997 as the main trading platform for German blue chip stocks at the FSE. Since the Xetra/FSE trading protocol is the data generating process for this study we will briefly describe its important features.[3]

Between an opening and a closing call auction - and interrupted by another mid-day call auction - Xetra/FSE trading is based on a continuous double auction mechanism with automatic matching of orders based on the usual rules of price and time priority. During pre- and post-trading hours it is possible to enter, revise and cancel orders, but order executions are not conducted, even if possible. During the year 2004, the Xetra/FSE hours extended from 9 a.m. C.E.T to 5.30 p.m. C.E.T. For blue chip stocks there are no dedicated market makers like the Specialists at the New York Stock Exchange (NYSE) or the Tokyo Stock Exchange's Saitori. For some small capitalized stocks listed in Xetra there may exist so-called Designated Sponsors - typically large banks - who are required to provide a minimum liquidity level by simultaneously submitting competitive buy and sell limit orders. In addition to the traditional limit and market orders, traders can submit so-called iceberg (or hidden) orders. An iceberg order is similar to a limit order in that it has pre-specified limit price and volume. The difference is that a portion of the volume is kept hidden from the other traders and is not visible in the open book.

Market orders and marketable limit orders which exceed the volume at the best quote are allowed to 'walk up the book'.[4] In other words, market orders are guaranteed immediate full execution, at the cost of incurring a higher price impact on the trades. This is one of the key features of the stylized theoretical trading environment upon which the econometric modeling is based, but which may not necessarily be found in the real world trading process.[5]

[3] The Xetra trading system resembles in many features other important limit order book markets around the world like Euronext, the joint trading platform of the Amsterdam, Brussels, Lisbon and Paris stock exchanges, the Hong Kong stock exchange described in Ahn et al. (2001), and the Australian stock exchange, described in Cao et al. (2004).

[4] A marketable limit order is a limit order with a limit price that makes it immediately executable against the current book. In our study, 'real' market orders (i.e. orders submitted without a upper or lower price limit) and marketable limit orders are treated alike. Henceforth, both real market orders and marketable limit orders are referred to as market orders.

[5] For example, Bauwens and Giot (2001) describe how the Paris Bourse's trading protocol converted the volume of a market order in excess of the depth at the best quote into a limit order at that price which enters

Xetra/FSE faces some local, regional and international competition for order flow. The FSE maintains a parallel floor trading system, which bears some similarities with the NYSE, and, like in the US, some regional exchanges participate in the hunt for liquidity. Furthermore, eleven out of the thirty stocks we analyze in our empirical study are also cross listed at the NYSE, as an ADR or, in the case of Daimler/Chrysler, as a globally registered share. However, the electronic trading platform clearly dominates the regional and international competitors in terms of market shares, at least for the blue chip stocks that we study in the present paper.

2.2 Data and descriptive analyses

The Frankfurt Stock Exchange granted access to a database containing complete information about Xetra open order book events (entries, cancelations, revisions, expirations, partial-fills and full-fills of market, limit, and iceberg orders) which occurred during the first three months of 2004 (January, 2nd - March, 31st). The sample comprises the thirty German blue chip stocks constituting the DAX30 index. Based on the event histories we perform a real time reconstruction of the order book sequences. Starting from an initial state of the order book, we track each change in the order book implied by entry, partial or full fill, cancelation and expiration of market, limit, and iceberg orders in order to re-construct the order book at each point in time. For the empirical methodology outlined below, we need to take snapshots of the order book entries whenever a market order triggers an execution against the book.

insert table 1 about here

Table 1 shows some characteristics of the cross section of stocks. It shows that the market for the thirty DAX stocks is quite active. Averaged across stocks, about 13,000 non-marketable limit orders per stock are submitted each day. Among those, almost 11,000 get canceled before execution. This indicates that the limit order traders closely monitor the book for profit opportunities which is in fact one of the core assumptions of the underlying theoretical model. The large trade sizes (on average over 40,000 euros per trade) indicate that Xetra/FSE is a trading venue for institutional traders and not a retail market. Averaged across stocks, 2,100 trades are executed per day. On average 15% of the order volume walks up the book, i.e. part of the order is matched by standing limit orders beyond the best bid and

the opposite side of the order book.

ask. Table 1 also reports average effective and realized spreads. The average effective spread is computed by taking two times the absolute difference of the transaction price of a trade and the prevailing midquote and averaging over all trades of a stock. Realized spreads are computed similarly, but instead of taking the prevailing midquote, the midquote five minutes after the trade is used.[6] To ensure comparability across stocks, we compute effective and realized spreads relative to the midquote prevailing at the time of the trade. Analyzing effective and realized spreads is a straightforward way to assess and compare transaction costs and adverse selection effects across stocks or trading venues. The realized spread can be viewed as a transaction costs measure that is purged of informational effects while the difference of effective and realized spread (referred to as price impact) is a natural measure for the amount of informational content of the order flow.[7] Average effective spreads range from 0.04 % to 0.13%. Realized spreads are considerably smaller. This implies that price impacts, computed as the difference between effective and realized spreads, are relatively large. In other words, a large fraction of the spread is due to informational order flow. This is not an unexpected result. In an open automated auction market there is no justification for inventory costs associated with market making or monopolistic power of a market maker, the other factors that may explain the spread. Furthermore, order submission fees, i.e. operational costs, are very small.

Table 1 shows that there is a considerable variation of price impacts, market capitalization and trading activity across stocks. The Spearman rank correlation between market capitalization and price impacts is -0.88 ($p-$value < 0.001) and the correlation between price impacts and daily number of trades is -0.87 ($p-$value < 0.001). Price impacts thus tend to be larger for smaller capitalized, less frequently traded stocks. We will come back to this result when discussing the empirical results based on the formal model.

[6]By choosing a five minutes lag we follow the previous literature, see e.g. SEC (2001)

[7]Boehmer (2004) and SEC (2001) conduct exhaustive comparisons of transaction costs and adverse selection effects in US exchanges based on effective and realized spread analyses.

3 Methodology

3.1 Theoretical background and standard moment conditions

Sandas (2001) develops a variant of Glosten's (1994) limit order book model with discrete price ticks and time priority rules. The model delivers equations which predict that order book depth and adverse selection effects are inversely related. The associated empirical methodology is rooted in economic theory, and delivers structural parameter estimates of transaction costs and adverse selection effects in a limit order book market. In the following we will briefly describe the assumptions of the basic model and the estimation strategy proposed in Sandas (2001). The fundamental asset value X_t is described by a random walk with innovations depending on an adverse selection parameter α, which gives the informativeness of a signed market order of size m_t,

$$X_{t+1} = \mu + X_t + \alpha m_t + \eta_{X,t+1}. \tag{1}$$

Negative values of m_t denote sell orders, positive values buy orders. Furthermore, it is assumed that $E(X_t) = 0$. $\eta_{X,t+1}$ is an innovation orthogonal to X_t. μ gives the expected change in the fundamental value. Market buy and sell orders are assumed to arrive with equal probability with a two-sided exponential density describing the distribution of order sizes m_t:

$$f(m_t) = \begin{cases} \frac{1}{2\lambda} e^{\frac{-m_t}{\lambda}} & \text{if } m_t > 0 \text{ (market buy)} \\ \frac{1}{2\lambda} e^{\frac{m_t}{\lambda}} & \text{if } m_t < 0 \text{ (market sell).} \end{cases} \tag{2}$$

Risk neutral limit order traders face a order processing cost γ (per share) and have knowledge about the distribution of market order size and the adverse selection component α, but not about the true asset price. They choose limit order prices and quantities such that their expected profit is maximized. If the last unit at any discrete price tick exactly breaks even, i.e. has expected profit equal to zero, the order book is in equilibrium.

Denote the ordered discrete price ticks on the ask (bid) side by p_{+k} (p_{-k}) with $k = 1, 2, \ldots$ and the associated volumes at these prices by q_{+k} (q_{-k}). Given these assumptions and setting $q_{0,t} \equiv 0$, the equilibrium order book at time t can recursively be constructed as follows:

$$\begin{aligned} q_{+k,t} &= \frac{p_{+k,t} - X_t - \mu - \gamma}{\alpha} - Q_{+k-1,t} - \lambda \quad k = 1, 2, \ldots \quad \text{(ask side)} \\ q_{-k,t} &= \frac{X_t + \mu - p_{-k,t} - \gamma}{\alpha} - Q_{-k+1,t} - \lambda \quad k = 1, 2, \ldots \quad \text{(bid side),} \end{aligned} \tag{3}$$

where $Q_{+k,t} = \sum_{i=+1}^{+k} q_{i,t}$ and $Q_{-k,t} = \sum_{i=-1}^{-k} q_{i,t}$. Equation (3) contains the model's key message. Order book depth and informativeness the order flow are inversely related. If the model provides a good description of the real world trading process, and if consistent estimates of the model parameters can be provided, one can use equation (3) to predict the evolution of the order book for a given stock and quantify adverse selection costs and their effect on order book depth.

Sandas (2001) proposes to employ GMM for parameter estimation and specification testing. Assuming mean zero random deviations from order book equilibrium at each price tick, and eliminating the unobserved fundamental asset value X_t by adding the resulting bid and ask side equations for quote $+k$ and $-k$, the following unconditional moment restrictions can be used for GMM estimation,

$$E\left(p_{+k,t} - p_{-k,t} - 2\gamma - \alpha\left(Q_{k,t} + 2\lambda + Q_{-k,t}\right)\right) = 0 \quad k = 1, 2, \ldots. \tag{4}$$

Since equation (4) follows from the assumption that the last (marginal) limit order at the respective quote has zero expected profit, it is referred to as 'marginal break even condition'. A second set of moment conditions results from eliminating X_t by subtracting the deviations from equilibrium depths at the kth quote at time $t+1$ and t and taking expectations which yields

$$\begin{aligned} E\left(\Delta p_{+k,t+1} - \alpha\left(Q_{k,t+1} - Q_{k,t}\right) - \mu - \alpha m_t\right) &= 0 \qquad k = 1, 2, \ldots \\ E\left(\Delta p_{-k,t+1} + \alpha\left(Q_{-k,t+1} - Q_{-k,t}\right) - \mu - \alpha m_t\right) &= 0 \qquad k = 1, 2, \ldots, \end{aligned} \tag{5}$$

where $\Delta p_{j,t+1} = p_{j,t+1} - p_{j,t}$. We refer to the equations in (5) as 'marginal update conditions'. They relate the expected changes in the order book to the market order flow. An obvious additional moment condition to identify the expected market order size is given by

$$E(|X_t| - \lambda) = 0. \tag{6}$$

Moment conditions (4), (5) and (6) can straightforwardly be exploited for standard GMM estimation a la Hansen (1982).

3.2 Revised moment conditions

3.2.1 Alternatives to the distributional assumption on market order sizes

Discussing the empirical performance of the Glosten/Sandas type models, Hasbrouck (2004) conjectures that, although the fundamental assumptions of the model may be correct, the exponential assumption on the market order size distribution of equation (2) may be inappropriate. This misspecification could be responsible for the discontenting empirical results which have been reported when the model is confronted with real world data. Of course, the exponential assumption is convenient both from a theoretical and an econometric perspective. It yields the closed form conditions for order book equilibrium (3) which, in turn, lend itself conveniently to GMM estimation. However, the parametric assumption can easily dispensed with and a straightforward nonparametric approach can be pursued for GMM estimation. In the appendix we show that the zero expected profit condition for the marginal unit at ask price p_{+k} can be written as

$$p_{+k} - \gamma - \alpha E\left[m | m \geq Q_{+k}\right] - X - \mu = 0.^{8} \tag{7}$$

Assuming of exponentially distributed market orders as in equation (2) we have $E\left[m|m \geq Q_{+k}\right] = Q_{+k} + \lambda$. Hence, equation (7) becomes

$$Q_{+k} = \frac{p_{+k} - X - \gamma - \mu}{\alpha}. \tag{8}$$

This is an alternative to equation (3) to describe order book equilibrium. Although the closed form expression implied by the parametric distributional assumption is convenient, it is not necessary that the econometric methodology has to rely on it. Instead, we can rewrite equation (7) to obtain

$$E\left[m|m \geq Q_{+k}\right] = \frac{p_{+k} - X - \gamma - \mu}{\alpha}. \tag{9}$$

In order to utilize equation (9) for GMM estimation, one can simply replace $E\left[m|m \geq Q_{+k}\right]$ by the conditional sample means $\widehat{E}\left[m|m \geq Q_{+k}\right]$. Since the number of observations will be large for frequently traded stocks (which is the case in our application), conditional expectations can be precisely estimated by the conditional sample means. Nonparametric equivalents of the marginal break even and update conditions (4) and (5) can be derived in the same fashion

[8] For notational brevity we omit the subscripts. Market order size m and fundamental price X are observed at time t, and the equation holds for any price tick $p_{+k,t}$ with associated cumulative volume $Q_{+k,t}$, $k = 1, 2 \ldots$.

as described in the previous section. GMM estimation becomes a bit more cumbersome and computer intensive than for the parametric specification, since evaluating the GMM objective function involves computation of the conditional sample means, but it is a straightforward exercise.

3.2.2 Replacing marginal by average profit conditions

The moment conditions derived from the zero expected profit assumption on the marginal unit are appropriate if the real world trading process features a continuous grid of prices and a continuously replenished limit order book. In such a frictionless setting the marginal zero profit condition should hold for each price/cumulated size combination. However, real world open order book trading systems feature discrete price ticks, FIFO time priority rules (orders with a given limit price that have been entered first are executed first) and delays in replenishing the book due to lags in processing the information about the state of the order book. The latter is reflected by the empirical fact that, also in our sample, not every feasible discrete price tick is endowed with nonzero order volume at any point in time. These 'holes in the order book' (zero volume price ticks in between two price ticks with nonzero volume) cannot be explained by the theoretical model as it would be rational to place an order at the zero volume quote tick thereby receiving price and time priority. Nevertheless, Sandas (2001) suggests to check the zero expected zero profit condition against the last unit of the limit order with the least time priority at each discrete price tick. This approach can be criticized on two grounds.

First, in order to justify the marginal zero profit assumption, one implicitly assumes a repetitive two phase trading process. In phase one, agents submit limit orders until the book is free of (expected) profit opportunities. The orders are sorted by price priority and, within the same price tick, by time priority. When the book has reached a Nash equilibrium, i.e. no agent wants to submit, revise or cancel her order, the order book should display no holes. In phase two, a single market order of a given size arrives (exogenously) and is executed against the equilibrium order book. After the respective standing limit orders have been executed against this market order, we go back to phase one, during which the book is replenished again until equilibrium is reached and another market order arrives and so forth. The rapid submission, cancelation and execution processes in a real world market do not conform to such a static trading protocol. The holes in the book are a clear indication for this statement.

Second, the zero expected profit condition for the marginal order implies nonzero expected profits for limit order units units that do not occupy the last position of the respective quote. As a consequence, the whole book offers positive expected profit and traders acting as market makers receive nonzero expected profits. If market making would provide nonzero expected profit opportunities, this would attract new entrants and competition between these would-be market makers would ultimately eliminate any profit opportunities.

We therefore suggest to replace the marginal zero profit condition by a more robust equilibrium condition that does not rely on the assumption that limit order traders immediately cancel or adjust all their orders which show negative expected profit on a marginal unit, and that also acknowledges the effect of market maker competition on expected profits. To derive the new equilibrium condition and the associated moment conditions, we retain most of the assumptions of the Glosten/Sandas framework. However, instead of evaluating the expected profit of the marginal profit for last unit at each quote k, it is assumed that the expected profit of the whole block of limit orders at any quote is zero. This assumption allows to differentiate between two types of costs associated with the submission of a limit order, a fixed cost component, like order submission and surveillance costs, and marginal (per share) costs, like execution or clearing fees and opportunity costs of market making. Note that these costs are not affected by adverse selection costs which are, as before, implicitly accounted for by the limit prices set by the limit order traders. In the appendix we show that the liquidity supply equations, which describe a limit order book that is in a zero expected profit equilibrium, can be written as

$$\begin{aligned} q_{+k,t} &= 2\left(\frac{p_{+k,t} - X_t - \gamma - \frac{\xi}{q_{+k,t}}}{\alpha} - \lambda\right) - Q_{+k-1,t} \quad k = 1, 2, \ldots \quad \text{(ask side)} \\ q_{-k,t} &= 2\left(\frac{X_t - p_{-k,t} - \gamma - \frac{\xi}{q_{-k,t}}}{\alpha} - \lambda\right) - Q_{-k+1,t} \quad k = 1, 2, \ldots \quad \text{(bid side)}. \end{aligned} \tag{10}$$

ξ denotes the fixed cost component which is assumed to be identical for each price tick in the order book. In order to derive the equations in (10), we have retained the parametric assumption about the distribution of trade sizes (see equation (2)).[9] The equations in (10)

[9]The liquidity supply equations can also be delivered under the nonparametric alternative described in 3.2.1.

are the counterpart of the equilibrium conditions (3) which result from the zero expected profit condition for the marginal orders.

Proceeding as described above, i.e. by assuming zero expected derivations from order book equilibrium and taking differences across quotes and over time, we can deliver analogous moment conditions to the marginal break even conditions in equation (4) and the marginal updating conditions in (5). Eliminating the unobserved fundamental asset value X_t by adding the bid and ask side equilibrium equations for quote $+k$ and $-k$ and assuming zero expected deviations from equilibrium yields the following unconditional moment restrictions which we refer to as average break even conditions,

$$E\left(\Delta p_{\pm k,t} - 2\gamma - \frac{\xi}{q_{+k,t}} - \frac{\xi}{q_{-k,t}} - \alpha\left(\frac{1}{2}Q_{+k,t} + 2\lambda + \frac{1}{2}Q_{-k,t}\right)\right) = 0 \quad k = 1, 2, \ldots, \qquad (11)$$

where $\Delta p_{\pm k,t} = p_{+k,t} - p_{-k,t}$. Subtracting deviations from equilibrium depths at the kth quote at time $t+1$ and t and taking expectation yields the following equations which we refer to as average update conditions,

$$\begin{aligned} E\left(\Delta p_{+k,t+1} - \frac{\xi}{q_{+k,t}} + \frac{\xi}{q_{+k,t-1}} - \frac{\alpha}{2}\left(Q_{+k,t+1} - Q_{+k,t}\right) - \mu - \alpha m_t\right) &= 0 \qquad k = 1, 2, \ldots \\ E\left(\Delta p_{-k,t+1} + \frac{\xi}{q_{+k,t}} - \frac{\xi}{q_{+k,t-1}} + \frac{\alpha}{2}\left(Q_{-k,t+1} - Q_{-k,t}\right) - \mu - \alpha m_t\right) &= 0 \qquad k = 1, 2, \ldots, \end{aligned} \qquad (12)$$

where $\Delta p_{j,t+1} = p_{j,t+1} - p_{j,t}$. The average break even and update conditions replace the marginal break even and update conditions of equation (4) and equation (5).

4 Empirical results

4.1 Performance comparisons

Using the DAX30 order book data we follow Sandas (2001) and estimate the model parameters exploiting the marginal break even conditions (4) and the marginal updating conditions (5) along with (6). To construct the moment conditions we use the respective first four best quotes, i.e. $k = 1, \ldots, 4$ on the bid and the ask side of the order book. This yields thirteen moment conditions: four break even conditions, eight update conditions, and the moment condition (6). Order sizes X_t are expressed in 1000 shares.

insert table 2 about here

Table 2 contains the first stage GMM results.[10] We report parameter estimates, $t-$statistics and the value of the GMM $J-$statistic with associated $p-$values. Under the null hypothesis that the moment conditions are correctly specified, the $J-$statistic is asymptotically χ^2 with degrees of freedom equal to the number of moment conditions minus the number of estimated parameters. The estimation results based on the Xetra data are in line with the central findings reported by Sandas (2001). They are a bit more favorable for the model, though. At least, for nine out of thirty stocks the model is not rejected at 1 % significance level while in Sandas' (2001) application the model was rejected for all stocks.[11] Non-rejection tends to occur for the less frequently traded stocks. The cross sectional correlation of the J-statistic and the daily number of trades is 0.87 (Spearman rank correlation, $p-$value < 0.001). Like in Sandas' (2001) application, the transaction cost estimates (γ) are significantly negative, a result that is difficult to reconcile with the underlying theoretical model. Hence, even with a data generating process that corresponds very close to the theoretical framework, the model does not seem to fit the data very well.

insert table 3 about here

insert table 4 about here

Tables and 3 and 4 report the results that are obtained when the modified moment conditions suggested in the previous section are used. As before, the first four quotes on each market side are used for the construction of break even and update conditions. Table 3 reports the estimation results for a specification that does not rely on a parametric assumption on the distribution of the market order size when constructing the marginal break even and the update conditions as described in section 3.2.1. The results reported in table 4 are obtained when using the average break even and update conditions (11) and (12) for GMM estimation, while maintaining the parametric assumption (2) about the trade size distribution. For each parametric specification, the moment condition of equation (6) is employed, too. The full set of eight update conditions is exploited.

[10]Two stage and iterated GMM estimates are quite similar and are not reported to conserve space.

[11]When only the visible part of the book is used, i.e. the limit order volume from the hidden orders is excluded, the results are worse. Only for one out of the 30 stocks, the model is not rejected. The visible book results are not reported to conserve space.

The estimates reported in table 3 show that abandoning the parametric assumption concerning the market order size distribution does not improve the results. Hasbrouck's (2004) conjecture that the distributional assumption might be responsible for the model's empirical failure is therefore not supported. Generally, the estimates of the adverse selection components, transaction costs and drift parameters do not change dramatically compared to the baseline specification. The transaction cost estimates remain negative, and only for five out of thirty stocks the model is not rejected at 1 % level of significance.[12]

Maintaining the distributional assumption, but using average break even conditions instead of marginal break even conditions, considerably improves the empirical performance. Table 4 shows that we have model non-rejection for 22 out of the 30 stocks at the 1% significance level (plus one borderline case with p-value = 0.008).[13] Especially for the larger capitalized, frequently traded stocks, the results improve noticeably. We obtain considerable smaller $J-$statistic values even for the stocks for which we reject the model at 1 % significance level. The transaction costs estimates are reasonable and broadly comparable with the relative realized spreads figures reported in table 1. For example, the estimation results imply that transaction costs account for 0.009% of the euro value of a median sized trade in DaimlerChrsyler. This value is quite comparable with the average relative realized spread which amounts to 0.01%. Recall that the realized spread is interpreted as a transaction costs measure which is purged of informational effects.

insert figure 1 about here

Figure 1 shows graphically the improved empirical performance delivered by the revised methodology. The figure depicts means an medians of implied and observed bid side price schedules of four selected stocks.[14] The results obtained from the baseline estimation which uses marginal moment conditions confirm the disturbing findings reported in Sandas (2001. The price schedules implied by the model estimates are below the observed price schedules at

[12]Using only the visible part of the book yields 3 non-rejections at 1 % level of significance, a slight improvement over the parametric specification.

[13]We obtain the same result when only the visible part of the book is used: 22 non-rejections with one borderline case at 1% significance level. Given that the baseline specification with marginal moment conditions was rejected for all stocks except one, the improvement of empirical performance brought about by using the average moment conditions is more noticeable when only the visible book is used.

[14]The figures look quite similar both for the ask side and the other stocks.

all relevant volumes. The economically implausible negative price discount at small volumes is caused by the negative transaction costs estimates. This suggests that the model is not only rejected on the grounds of statistical significance, but that fundamentally fails to explain the data. The model does a bad job even in describing the 'average' state of the order book. However, figure 1 shows that when working with average break even and update conditions the empirical performance of the model is considerably improved. Especially the median observed price schedules correspond closely to those implied by the model.[15]

These results indicate that the ability of Glosten's theoretical framework to explain real world order book variation is greater than previously thought. However, assuming that a very volatile limit order book, like for example the DaimlerChrysler book with almost 19,000 limit order submissions and almost 16,000 cancelations per day, is in a no-profit equilibrium as described by the marginal break even conditions is too restrictive. Adhering to the basic theoretical framework, but using average break even conditions seems to be a more sensible strategy to model an active limit order book market.

4.2 Cross sectional analyses

Encouraged by the improved empirical performance of the revised methodology, this section uses the estimation results reported in table 4 to conduct a cross sectional analysis of liquidity supply and adverse selection costs in the Xetra limit order book market. To ensure comparability across stocks, we follow a suggestion by Hasbrouck (1991) and standardize the adverse selection component α by computing

$$\tau = \frac{\alpha \cdot \overline{m}}{\overline{P}}, \tag{13}$$

where $\overline{m}$ is the sample average absolute, i.e. non-signed, trade size expressed in number of shares. $\overline{P}$ is the sample average of the midquote of the respective stock. τ (times 100) approximates the percentage change of the stock price caused by a trade of 'average' size. This a relative measure which is comparable across stocks. The stock specific τ estimates

[15] We also have estimated a specification that combines the nonparametric approach towards trades sizes and average moment conditions, but the results (not reported) are not improved compared to the parametric version. In this version, model acceptance occurs for 17 out of 30 stocks (16 out of 30 when only the visible part of the book is used). The following analysis therefore focuses on the parametric specification using average moment conditions.

are reported in the last column of table 4. In the following subsections we study the relation of τ and market capitalization, trading frequency, liquidity supply and alternative adverse selections measures.

4.2.1 Adverse selection effects, market capitalization and frequency of trading

In their seminal papers Hasbrouck (1991) and Easley et al. (1996) have reported empirical evidence that adverse selection effects are more severe for smaller capitalized stocks. Easley et al. (1996) use a formal model assuming a Bayesian market maker who updates quotes according to the arrival of trades while Hasbrouck (1991) estimates a vector autoregression (VAR) involving trade and midquote returns. Both methodologies have modest data requirements. To estimate the model by Easley et al. (1996) one only needs to count the number of buyer and seller initiated trades per trading day to estimate the probability of informed trading (PIN), the central adverse selection measure in this framework. As it allows a structural interpretation of the model parameter estimates the methodology is quite popular in empirical research. Hasbrouck's VAR methodology is not based on a formal model, but the reduced form VAR equations are compatible with a general class of microstructure models. The adverse selection measure is given by the cumulative effect of a trade innovation on the midquote return. To estimate the model, standard trade and quote data are sufficient.

Both methodologies are not specifically designed for limit order markets, but rather for market maker systems. Accordingly, their main applications have been to analyze NYSE and NASDAQ stocks. In the present paper, the data generating process, the theoretical background and the empirical methodology are quite different. However, we reach the same conclusion as Hasbrouck (1991) and Easley et al. (1996). When computing the Spearman rank correlation of the market capitalization and the estimated standardized adverse selection component (τ) we obtain a value of -0.90 ($p-$value < 0.001). The correlation of τ and the daily number of trades is -0.92 ($p-$value < 0.001), and the correlation of τ and the daily turnover is -0.95 ($p-$value < 0.001). The estimation results thus confirm the previous evidence also for a open limit order market: Adverse selection effects are more severe for smaller capitalized stocks.

4.2.2 Adverse selection and liquidity supply

Many theoretical market microstructure models predict that liquidity supply and informed order flow are inversely related. As the standard framework for microstructure models is a stylized NYSE trading process with a single market maker quoting best bid and ask prices and associated depths (the 'inside market'), liquidity in those models is usually measured by the inside spread set by the specialist/market maker. Sequential trading models like Easley et al. (1996) and spread decomposition models like Glosten and Harris (1988) predict that liquidity (as measured by the spread) and informed order flow are inversely related. In the presence of informed order flow, the market maker widens the spread in order to balance the losses that occur when trading with superiorly informed agents. More informed order flow thus implies reduced liquidity. Empirical analyses of specialist markets have confirmed this prediction. The results reported in table 5 provide evidence that the inverse relation of inside spread and informed order flow also holds for open limit order book markets in which limit order traders, instead of specialists, determine the inside market. The table reports the cross sectional correlation (Spearman rank correlation) of the standardized adverse selection component τ and the effective, quoted, and the realized spreads. Effective and quoted spreads and τ are strongly positively correlated while the correlation with the realized spread and τ is insignificantly different from zero. Given the interpretation of the realized spreads as a transaction costs measure which is purged of any informational effects, this is in line with the theoretical prediction. Only the effective and quoted spreads should be effected by adverse selection effects.

In a transparent open limit order market framework, it is informative to analyze liquidity also beyond the inside market (see Beltran et al. (2004) and Cao et al. (2004) for empirical studies of the informational content of the order book beyond the best quotes). Equation (3) shows that in Sandas' (2001) marginal zero expected profit equilibrium, book liquidity (measured by the depth at ticks from the inside market) is inversely related to the adverse selection component α. Other things being equal, stocks for which informational order flow is high are predicted to be less liquid than low α stocks.

insert table 5 about here

The cross sectional results reported in table 5 strongly confirm this prediction. In order to measure liquidity displayed in the order book and beyond the inside market we employ a pre-trade book liquidity measure similar to those proposed in Irvine et al. (2000) and Gomber et al. (2004). The basic idea is to compare the per-share price of a time t buy or sell order of volume v with the prevailing best ask or bid price, respectively. The per-share price obtained when selling v shares at time t can be computed as

$$b_t(v) = \frac{\sum_k b_{k,t} v_{k,t}}{v}, \tag{14}$$

where v is the volume executed at k different unique bid prices $b_{k,t}$ with corresponding volumes $v_{k,t}$ standing in the limit order book at time t (this takes into account that the order can 'walk up the book'). The unit price $a_t(v)$ of a buy of size v at time t can be computed analogously. To ensure comparability across stocks, we relate the per-share prices to the best quotes, viz

$$ap_t(v) = \frac{a_t(v) - a_t(1)}{a_t(1)} \cdot 10,000 \tag{15}$$

and

$$bp_t(v) = \frac{b_t(1) - b_t(v)}{b_t(1)} \cdot 10,000. \tag{16}$$

We refer to $ap_t(v)$ as the ask price impact and to $bp_t(v))$ as the bid price impact. These price impacts serve as natural liquidity measures for an open order book system. They account for the bi-dimensionality of liquidity supply (price and volume), and are comparable across stocks. For the purpose of this study we set $v = 100,000$ euros. To obtain stock specific measures we take sample averages over all order book snapshots. Taking absolute values and averaging over the buy and sell side measure, we obtain a single stock specific book liquidity measure, which we refer to as BLM. The results reported in table 5 strongly supports the hypothesis that adverse selection effects and book liquidity beyond the best quotes are negatively related. The relation is even stronger than for liquidity measured by the inside spread. The Spearman correlation of the standardized adverse selection component τ and BLM is 0.98 ($p-$value < 0.001), compared to 0.76 ($p-$value < 0.001) for quoted spread and τ. Stocks for which we estimate a high adverse selection component are also the less liquid stocks.

4.2.3 Ad hoc versus model-based estimates of adverse selection effects in a limit order book market

In this subsection we investigate whether the adverse selection estimates obtained from the formal model and those delivered by the simple analysis of effective and realized spreads (see section 2) point in the same direction. The two methodologies differ in two main aspects. First, the estimation of adverse selection components by taking the difference of effective and realized spread is not based on a specific theoretical model. The economic intuition behind the methodology, however, is quite clear, which explains the popularity of the approach. A large difference between effective and realized spread indicates informational content of the order flow as the midquote tends to move in the direction of the trade. If a market buy (sell) order initiates a trade at time t, then the midquote five minutes after the trade is on average above (below) the time t midquote. By contrast, the estimates of the standardized adverse selection component reported in table 4 are based on a formal model assuming rational limit order traders who place their order submissions explicitly taking into account the amount of informativeness of the order flow. Second, computation of price impacts by taking the difference of effective and realized spread only requires publicly available trade and (best) quote data. To obtain the estimates in the formal framework considered in this paper, reconstructed order book data are needed. The latter methodology thus uses richer data, which are, however, more difficult to obtain.

But do the two different methodologies lead to the same conclusions? To answer this question we compute the Spearman rank correlation between the standardized adverse selection components (τ) reported in table 4 and the difference of effective and realized spreads. The cross sectional correlation is 0.95, which indicates that the two different methodologies point in the same direction. This indicates the robustness of the estimation results of the formal model and also provides a theoretical justification for using the popular ad hoc method for the analysis of adverse selection effects in limit order book markets.

5 Conclusion and outlook

An increasing number of financial assets trade in limit order markets. These markets can be characterized by the following keywords: Transparency, anonymity and endogenous liquidity supply. Transparency, because they offer a more or less unobstructed view on the liquidity supplied on the offer and buy side. Anonymity, because prior to a trade the identity of neither those agents supplying nor of those traders demanding liquidity is revealed. Endogenous liquidity supply, because typically no dedicated market makers responsible for quoting bid and ask prices are present. The question how liquidity quality and price formation in such a trading design is affected by informed order flow is a crucial one, both from a theoretical and a practical point of view. Glosten (1994) has put forth a formal model that describes how an equilibrium order book emerges in the presence of potentially informed order flow. Sandas (2001) has confronted the Glosten model with real world data and reported quite discouraging results. His findings suggest that Glosten's model contains too many simplifying assumptions in order to provide a valid description of the intricate real world trading processes in limit order markets.

This paper shows that the ability of Glosten's basic framework to explain real world order book formation is greater than previously thought.We estimate the model using data produced by a DGP that closely corresponds to the Glosten's theoretical framework and confirm the previous finding that the baseline specification put forth by Sandas (2001) is generally rejected. However, relaxing the assumption about marginal zero profit order book equilibrium in favor of a weaker equilibrium condition, considerably improves the empirical performance. The equilibrium condition proposed in this paper does not assume that traders immediately cancel a marginal order that shows non-positive expected profit. It also acknowledges the fact that competition between potential market makers will render the expected profit offered by the whole book ultimately to zero (after accounting for opportunity costs). Employing the revised econometric methodology, formal specification tests now accept the model in the vast majority of cases at conventional significance levels. A comparison of implied and observed order book schedules shows that the model estimated on the revised set of moment conditions fits the data quite well. We conclude that Glosten's theoretical framework can also be transferred into a quite useful empirical model.

On the other hand, the conjecture put forth by Hasbrouck (2004), which states that the distributional assumption regarding the market order sizes is responsible for the empirical model failure is not supported. The paper has developed a straightforward way to circumvent the restrictive distributional assumption and proposes a nonparametric alternative. However, this modification does not deliver an improved empirical performance.

Given the overall encouraging results, the empirical methodology is employed for an analysis of liquidity supply and adverse selection costs in a cross section of stocks traded in one of the largest European equity markets. The main results can be summarized as follows:

- We have provided new evidence, from a limit order market, that adverse selection effects are more severe for smaller capitalized, less frequently traded stocks. This corroborates the results of previous papers dealing with a quite different theoretical background, empirical methodology and market structure.

- The empirical results support one of the main hypothesis of the theory of limit order markets, namely that book liquidity and adverse selection effects are inversely related.

- The adverse selection component estimates implied by the structural model and ad hoc measures of informed order flow which are based on a comparison of effective and realized spreads point in the same direction.

The latter result is useful, because is not always possible to estimate the structural model, most often because of the lack of suitable data.The result also points towards the robustness of the structural model.

Avenues for further research stretch in various directions. The results reported in this paper have vindicated the empirical relevance the Glosten type market order model. Practical issues in market design can thus be empirically addressed based on a sound theoretical framework. The revised methodology could be employed to evaluate changes in trading design on liquidity quality, with the advantage that the results can be interpreted on a sound theoretical basis. A comparison of (internationally) cross listed stocks seems also promising, especially after the NYSE's move towards adopting the key feature of a open limit order market, the public display of the limit order book. An interesting question would be to investigate whether the recently reported failures of cross listings (in terms of insufficient trading volume in the foreign markets) are due to market design features that aggravate potential adverse selection effects.

Second, a variety of methodological extensions could be considered. Sandas (2001) has already addressed the issue of state dependence of the model parameters. He used a set of plausible instruments to scale the model parameters. Recent papers on price impacts of trades point to alternative, powerful instruments that could be used, and which might improve the empirical performance and explanatory power. For example, Dufour and Engle (2000) have emphasized the role of time between trades within Hasbrouck's (1991) VAR framework. As the Glosten/Sandas type model considered in this paper is also estimated on irregularly spaced data, it seems natural to utilize their findings. Furthermore, the exogeneity of the market order flow is a restrictive assumption that should be relaxed. Gomber et al. (2004) and Coppejans et al (2003) show that market order traders time their trades by submitting larger trade sizes at times when the book is relatively liquid. Hence, using the liquidity state of the book as a scaling instrument for the expected order size parameter seems a promising strategy. Finally, as in many GMM applications, the number of moment conditions that are available are large, and the difficult task is to pick both relevant and correct moment conditions. Recent contributions by Andrews (1999) and Hall and Peixe (2001) could be utilized to base the selection of moment conditions on a sound methodological basis.

A Appendix: Derivation of revised moment conditions

This section outlines the background for the revised set of moment conditions describing order book equilibrium. We start by writing the zero expected profit condition for one unit of a limit sell order as

$$E(R_t - X_{t+1}) = 0, \tag{A.1}$$

where R_t denotes the net revenue (minus transaction costs) received from selling one unit of a limit order at price p_t to a market order trader who submitted a market buy order of size m_t.[16] X_{t+1} denotes the fundamental value of the stock after the arrival the (buy) market order. X_{t+1} depends on the current value X_t and the signed market order size m_t, i.e. $X_{t+1} = g(m_t, X_t)$. For brevity of notation we henceforth omit the time t subscripts whenever it is unambiguous to do so.

The expected profit of the market order depends on the position of the limit order in the order queue and the distribution of market orders, i.e. we can write equation (A.1) as

$$\int_Q^\infty (R - g(m, X)) f(m) dm, = 0. \tag{A.2}$$

Q is the cumulated sell order volume standing in the book before the considered limit order unit and $f(m)$ denotes the probability density function of m. Alternatively, equation (A.2) can be written as

$$(R - E\left[g(m, X) | m \geq Q\right]) \cdot P\left(m \geq Q\right) = 0. \tag{A.3}$$

Assuming the linear specification in equation (1) for $g(m, X)$, and dividing by the unconditional probability, $P\left(m \geq Q\right)$, equation (A.3) simplifies to

$$R - \alpha E\left[m | m \geq Q\right] - X - \mu \cdot = 0. \tag{A.4}$$

Equation (A.4) highlights that the expected profit of a limit order trader depends on the upper tail expectation of the market order distribution.

Assuming exponentially distributed market order sizes as in equation (2) we have

$$E\left[m | m \geq Q\right] = Q + \lambda \tag{A.5}$$

Using $R = p - \gamma$ this yields

$$Q = \frac{p - X - \gamma - \mu}{\alpha} - \lambda, \tag{A.6}$$

[16]The exercise is analogous for the bid side, but to conserve space, we focus on the sell side of the book.

which a generalized form of equation (3). Without the distributional assumption, the equivalent of equation (A.6) is

$$E\left[m|m \geq Q\right] = \frac{p - X - \gamma - \mu}{\alpha} \tag{A.7}$$

Replacing $E\left[m|m \geq Q\right]$ by the conditional sample mean $\widehat{E}\left[m|m \geq Q\right]$, i.e. the observed upper tail market order distribution in the sample, one can construct update and break even moment conditions for GMM estimation which do not require a parametric assumption of market order sizes.

So far, the results are valid for an order book with a continuous price grid. We now focus on a specific offer side quote with price p_{+k} and corresponding limit order volume q_{+k}. Abstracting from the discreteness of limit order size shares and assuming that the execution probabilities for all units at the quote tick p_{+k} are identical, we calculate the expected profit of all limit orders with limit price p_{+k} by integrating the left hand side of equation, (A.4), viz[17]

$$\int_{Q_{+k-1}}^{Q_{+k}} \left(p_{+k} - \gamma - \alpha E\left[m|m \geq Q\right] - X - \mu\right) dQ \cdot P\left(m \geq Q_{+k-1}\right). \tag{A.8}$$

Assuming exponentially distributed order sizes and subtracting quote specific fixed execution costs ξ yields the total expected profit of the limit order volume at price p_{+k}. Dividing by the volume at quote q_{+k}, yields the average expected profit per share at the $+k$th quote ,

$$\left(p_{+k} - X - \mu - \gamma - \frac{\xi}{q_{+k}} - \alpha(Q_{+k} + \lambda - \frac{q_{+k}}{2})\right) \cdot P\left(m \geq Q_{+k-1}\right) \tag{A.9}$$

In the main text we motivate that in an equilibrium the expected profit of any quote should be zero. This implies that

$$p_{+k} - X - \mu - \gamma - \frac{\xi}{q_{+k}} - \alpha(Q_{+k} + \lambda - \frac{q_{+k}}{2}) = 0. \tag{A.10}$$

Reordering equation (A.10) yields of the average profit conditions (10) from which average break even and update conditions can be derived as described in the main text.

[17]The same result can be derived using the precise probabilities and a first-order Taylor approximation for the emerging exponential terms.

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company name	ticker symbol	turnover	mkt. cap.	$\overline{m}$	% aggr. trades	trades per day	LO sub.	LO canc.	$\overline{P}$	eff. spread	real. spread
TUI	TUI	26281175	2025	24723	17.6	1063	6767	5714	18.7	0.125	0.015
CONTINENTAL	CONT	25627638	4060	25574	13.5	1002	8036	7052	31.6	0.092	-0.011
MAN	MAN	27685031	2434	26189	13.0	1057	7214	6235	27.7	0.096	0.003
METRO	MEO	38874669	5018	31480	15.7	1235	7975	6702	35.0	0.089	0.000
LINDE	LIN	22378772	3448	24971	15.8	896	8342	7454	43.6	0.080	-0.009
LUFTHANSA	LHA	43946809	4548	32504	11.9	1352	8079	6780	14.2	0.111	0.022
FRESENIUS	FME	12850947	1944	20680	16.7	621	5764	5195	54.0	0.098	0.010
THYSSEN-KRUPP	TKA	37892493	6450	30017	11.3	1262	7864	6672	15.9	0.111	0.029
DEUTSCHE POST	DPW	43836617	6806	33330	11.0	1315	6861	5666	18.2	0.097	0.018
BAY.HYPO-VEREINSB.	HVM	98351090	6629	50783	15.0	1937	10204	8293	18.7	0.098	0.019
COMMERZBANK	CBK	53171668	7569	36659	12.6	1450	11922	10476	15.4	0.100	0.023
ADIDAS-SALOMON	ADS	31976047	4104	32635	20.1	980	8057	7105	92.6	0.070	-0.002
DEUTSCHE BOERSE	DB1	35696903	4847	36359	18.4	982	6598	5698	46.9	0.075	0.003
HENKEL	HEN3	18174548	3682	25904	16.6	702	7989	7306	65.9	0.077	0.005
ALTANA	ALT	30985416	3338	28310	18.9	1095	7718	6609	48.6	0.079	0.008
SCHERING	SCH	51413053	7055	33756	16.2	1523	9111	7669	40.8	0.071	0.004
INFINEON	IFX	146462315	4790	52331	8.6	2799	10320	7744	11.6	0.104	0.040
BAYER	BAY	88776121	15911	36994	12.4	2400	15258	12988	23.1	0.076	0.012
RWE	RWE	97655566	12653	42203	13.0	2314	14438	12355	33.8	0.062	0.002
BMW	BMW	87854358	12211	41639	14.4	2110	14736	12764	34.7	0.060	0.003
VOLKSWAGEN	VOW	104249843	9688	40963	16.0	2545	13474	11273	39.2	0.056	0.004
BASF	BAS	124434537	25425	48236	13.8	2580	18211	15898	43.3	0.051	0.002
SAP	SAP	184628162	27412	65795	21.9	2806	19733	17095	131.5	0.049	0.001
E.ON	EOA	160625983	33753	55950	13.6	2871	18899	16468	52.5	0.048	0.003
MUENCH.RUECK	MUV2	207353230	16396	60534	20.7	3425	20154	16894	93.9	0.049	0.005
DAIMLERCHRYSLER	DCX	187737846	30316	56736	14.5	3309	18722	15919	36.4	0.055	0.010
DETUSCHE TELEKOM	DTE	350627866	34858	78884	5.0	4445	14498	11009	15.7	0.072	0.031
DEUTSCHE BANK	DBK	309282831	38228	78083	19.3	3961	23169	19772	67.2	0.044	0.004
ALLIANZ	ALV	289980556	33805	64114	21.4	4523	29791	25882	100.1	0.049	0.010
SIEMENS	SIE	321704299	52893	72831	16.7	4418	23659	19920	64.0	0.041	0.006
Average		108683880	14076	42972	15.2	2099	12785	10887	44.5		

Table 1: Sample descriptives.*Mkt. cap.* is the market capitalization in million euros at the end of December 2003, $\overline{m}$ is the average trade size (in euros). *%Aggr. trades* gives the percentage of total trading volume that has not been executed at the best prices (that is, the order walked up the book). *Turnover* is the average trading volume in euros per trading day, *trades per day* is the average number of trades per day, *LO sub.* and *LO canc.*, respectively, denote the average number of non-marketable limit order order submissions and cancelations per day. $\overline{P}$, *eff. spread* and *real. spread* refer to the sample averages of midquote, effective spread and realized spread, respectively. The average effective spread is computed by taking two times the absolute difference of the transaction price of a trade and the prevailing midquote and averaging over all trades of a stock. The average realized spread is computed similarly, but instead of taking the prevailing midquote, we use the midquote five minutes after the trade. To ensure comparability across stocks, we compute effective and realized spreads relative to the midquote prevailing at the time of the trade and multiply by 100 to obtain a % figure. The table is sorted in descending order by the difference of effective and realized spread. The sample ranges from January 2, 2004 to March 31, 2004.

ticker	α	γ	λ	μ	$J(9)$	$p-$value
LIN	0.0178	-0.0182	0.5724	0.0003	0.2	1.000
	(148.3)	(56.1)	(162.1)	(2.7)		
FME	0.0332	-0.0227	0.3840	0.0000	0.6	1.000
	(105.5)	(31.8)	(118.3)	(0.1)		
LHA	0.0014	-0.0071	2.3132	0.0001	5.2	0.819
	(258.7)	(80.7)	(174.6)	(3.8)		
MEO	0.0096	-0.0147	0.9055	0.0000	7.8	0.557
	(190.4)	(68.0)	(196.0)	(0.2)		
HEN3	0.0329	-0.0182	0.3938	-0.0002	7.9	0.540
	(122.2)	(38.4)	(139.5)	(1.6)		
DPW	0.0017	-0.0067	1.8322	-0.0001	8.7	0.464
	(235.9)	(65.1)	(175.4)	(2.6)		
MAN	0.0066	-0.0130	0.9432	0.0003	15.0	0.090
	(144.7)	(53.7)	(162.9)	(4.4)		
TUI	0.0041	-0.0098	1.3189	-0.0001	17.5	0.042
	(176.8)	(55.0)	(149.6)	(2.2)		
CONT	0.0098	-0.0155	0.8143	0.0002	20.2	0.017
	(148.2)	(59.8)	(168.0)	(2.0)		
ALT	0.0170	-0.0136	0.5780	-0.0002	25.7	0.002
	(170.0)	(52.0)	(170.6)	(1.7)		
BMW	0.0039	-0.0096	1.2012	-0.0001	30.8	0.000
	(246.4)	(86.3)	(233.5)	(2.6)		
DB1	0.0094	-0.0121	0.7735	0.0001	39.2	0.000
	(151.5)	(43.4)	(137.4)	(1.0)		
ADS	0.0438	-0.0180	0.3528	-0.0002	61.9	0.000
	(147.5)	(35.5)	(163.6)	(1.0)		
CBK	0.0011	-0.0047	2.3990	0.0000	63.8	0.000
	(225.8)	(62.1)	(176.9)	(1.9)		
RWE	0.0040	-0.0101	1.2440	0.0001	97.3	0.000
	(287.2)	(95.9)	(243.1)	(3.0)		
SCH	0.0078	-0.0103	0.8237	0.0000	119.6	0.000
	(181.3)	(51.5)	(201.0)	(0.4)		
TKA	0.0019	-0.0072	1.9002	0.0000	137.6	0.000
	(236.3)	(73.2)	(184.0)	(1.0)		
VOW	0.0046	-0.0110	1.0458	0.0001	194.8	0.000
	(31.9)	(15.5)	(230.5)	(0.1)		
BAS	0.0043	-0.0086	1.1199	0.0000	279.6	0.000
	(313.1)	(92.1)	(277.7)	(0.8)		
IFX	0.0003	-0.0032	4.5261	0.0000	306.4	0.000
	(364.2)	(84.6)	(195.8)	(0.2)		
DTE	0.0002	-0.0013	5.0455	0.0000	319.4	0.000
	(537.6)	(57.2)	(259.4)	(0.1)		
DCX	0.0023	-0.0058	1.5617	0.0001	325.2	0.000
	(270.0)	(64.6)	(288.4)	(5.5)		
BAY	0.0020	-0.0048	1.6328	0.0000	431.6	0.000
	(335.7)	(76.9)	(261.7)	(1.3)		
HVM	0.0010	-0.0037	2.8319	0.0000	483.7	0.000
	(166.4)	(41.3)	(165.8)	(0.6)		
EOA	0.0047	-0.0075	1.0663	0.0000	552.4	0.000
	(301.7)	(75.6)	(284.5)	(0.8)		
SAP	0.0297	-0.0153	0.5022	0.0005	1094.1	0.000
	(287.9)	(58.3)	(275.5)	(5.0)		
MUV2	0.0140	-0.0108	0.6467	0.0000	1110.4	0.000
	(272.1)	(63.6)	(285.4)	(0.7)		
DBK	0.0051	-0.0066	1.1503	0.0000	1997.7	0.000
	(359.7)	(71.4)	(297.3)	(0.7)		
ALV	0.0146	-0.0088	0.6439	-0.0002	2041.7	0.000
	(322.1)	(52.7)	(335.7)	(4.0)		
SIE	0.0042	-0.0050	1.1429	0.0001	3323.0	0.000
	(408.6)	(56.8)	(339.2)	(1.9)		

Table 2: First stage GMM results baseline specification. 2×4 quotes from the bid and ask side of the complete book (visible and hidden part) are used to construct update and break even conditions derived from the zero marginal expected profit condition as in Sandas (2001). The numbers in parentheses are $t-$values. The fifth and sixth column report the GMM J statistic and the associated $p-$value. The stocks are sorted by ascending $p-$value of the $J-$statistic.

ticker	α	γ	μ	$J(9)$	$p-$value
FME	0.0210	-0.0149	0.0000	0.3	1.000
	(107.3)	(24.2)	(0.2)		
HEN3	0.0242	-0.0138	-0.0001	6.2	0.715
	(125.8)	(31.9)	(1.0)		
TUI	0.0031	-0.0100	-0.0001	12.6	0.183
	(200.3)	(63.4)	(1.8)		
LIN	0.0138	-0.0160	0.0002	16.5	0.058
	(167.5)	(56.5)	(2.3)		
ALT	0.0137	-0.0131	-0.0001	24.9	0.003
	(190.9)	(56.5)	(1.5)		
BMW	0.0029	-0.0089	-0.0001	27.3	0.001
	(272.2)	(87.0)	(2.3)		
VOW	0.0036	-0.0116	0.0000	30.6	0.000
	(40.3)	(20.6)	(0.1)		
DB1	0.0062	-0.0089	0.0001	39.2	0.000
	(141.8)	(32.8)	(0.8)		
LHA	0.0011	-0.0072	0.0001	42.7	0.000
	(265.3)	(85.7)	(3.2)		
SCH	0.0061	-0.0098	0.0000	45.1	0.000
	(209.4)	(56.8)	(0.4)		
HVM	0.0008	-0.0058	0.0000	46.1	0.000
	(203.5)	(72.1)	(0.4)		
ADS	0.0333	-0.0137	-0.0001	46.7	0.000
	(164.2)	(31.7)	(0.8)		
MEO	0.0079	-0.0139	0.0000	54.2	0.000
	(208.8)	(71.4)	(0.2)		
CONT	0.0074	-0.0135	0.0001	63.8	0.000
	(167.3)	(59.1)	(1.8)		
RWE	0.0028	-0.0082	0.0001	94.9	0.000
	(287.7)	(84.3)	(2.6)		
MAN	0.0052	-0.0127	0.0003	98.8	0.000
	(164.5)	(59.4)	(4.0)		
DTE	0.0001	-0.0015	0.0000	232.8	0.000
	(604.0)	(72.0)	(0.1)		
BAS	0.0032	-0.0069	0.0000	238.8	0.000
	(308.3)	(78.6)	(0.4)		
IFX	0.0002	-0.0045	0.0000	262.4	0.000
	(440.7)	(123.2)	(0.1)		
DPW	0.0015	-0.0079	-0.0001	370.8	0.000
	(271.7)	(81.3)	(2.2)		
CBK	0.0010	-0.0066	0.0000	420.6	0.000
	(270.4)	(91.5)	(1.9)		
DCX	0.0016	-0.0045	0.0001	448.9	0.000
	(277.1)	(53.2)	(3.7)		
BAY	0.0014	-0.0034	0.0000	524.8	0.000
	(305.2)	(54.6)	(1.3)		
EOA	0.0033	-0.0054	0.0000	643.6	0.000
	(329.2)	(62.7)	(0.5)		
SAP	0.0230	-0.0124	0.0003	690.2	0.000
	(320.7)	(54.4)	(4.2)		
TKA	0.0016	-0.0080	0.0000	738.2	0.000
	(264.3)	(87.6)	(0.9)		
MUV2	0.0103	-0.0090	0.0000	739.2	0.000
	(292.1)	(58.7)	(0.4)		
DBK	0.0038	-0.0059	0.0000	1199.1	0.000
	(390.3)	(70.6)	(0.5)		
ALV	0.0108	-0.0068	-0.0001	1617.4	0.000
	(346.4)	(44.0)	(3.4)		
SIE	0.0034	-0.0051	0.0001	2080.3	0.000
	(474.1)	(66.9)	(1.7)		

Table 3: First stage GMM results for the nonparametric specification. 2×4 quotes from the bid and ask side of the complete book (visible and hidden part) are used to construct update and break even conditions derived from the zero marginal expected profit condition as in Sandas (2001). For the construction of the moment conditions, the empirical distribution of the market order sizes is used instead of the exponential distribution. The stocks are sorted by ascending $p-$value of the $J-$statistic.

ticker	α	γ	λ	ξ	μ	$J(8)$	$p-$value	$\tau(\%)$
HEN3	0.0427	-0.0802	0.3938	0.0082	-0.0003	0.0	1.000	0.0254
	(3.4)	(0.9)	(139.5)	(0.8)	(0.9)			
IFX	0.0003	0.0031	4.5261	-0.0044	0.0000	0.2	1.000	0.0117
	(263.8)	(25.2)	(195.8)	(14.4)	(0.1)			
DBK	0.0045	0.0117	1.1503	-0.0026	0.0000	0.2	1.000	0.0078
	(147.6)	(23.0)	(297.3)	(20.0)	(0.5)			
TUI	0.0040	-0.0014	1.3189	-0.0002	-0.0001	0.4	1.000	0.0282
	(156.6)	(2.7)	(149.6)	(1.6)	(2.3)			
FME	0.0393	-0.0634	0.3840	0.0056	0.0000	0.5	1.000	0.0279
	(9.0)	(1.8)	(118.3)	(1.6)	(0.0)			
ADS	0.0423	0.0072	0.3528	-0.0008	-0.0002	0.6	1.000	0.0161
	(62.0)	(1.5)	(163.6)	(1.9)	(1.0)			
SAP	0.0238	0.0452	0.5022	-0.0049	0.0004	0.7	1.000	0.0091
	(40.8)	(9.5)	(275.5)	(9.1)	(3.0)			
LIN	0.0185	-0.0157	0.5724	0.0013	0.0003	0.8	0.999	0.0243
	(92.1)	(10.0)	(162.1)	(6.3)	(2.7)			
SIE	0.0037	0.0113	1.1429	-0.0026	0.0001	1.1	0.997	0.0066
	(162.5)	(29.3)	(339.2)	(23.7)	(1.7)			
MUV2	0.0125	0.0175	0.6467	-0.0026	0.0000	1.4	0.994	0.0086
	(135.8)	(16.1)	(285.4)	(14.6)	(0.5)			
HVM	0.0010	0.0060	2.8319	-0.0032	0.0000	1.6	0.991	0.0145
	(120.0)	(15.2)	(165.8)	(12.0)	(0.4)			
DB1	0.0090	0.0040	0.7735	-0.0009	0.0001	2.9	0.938	0.0149
	(93.6)	(2.7)	(137.4)	(3.8)	(1.0)			
ALV	0.0123	0.0239	0.6439	-0.0033	-0.0002	3.6	0.889	0.0079
	(112.7)	(21.4)	(335.7)	(18.6)	(3.0)			
DCX	0.0022	0.0037	1.5617	-0.0015	0.0001	3.8	0.875	0.0094
	(207.0)	(16.0)	(288.4)	(15.7)	(4.6)			
DTE	0.0002	0.0042	5.0455	-0.0061	0.0000	5.2	0.741	0.0064
	(351.4)	(58.4)	(259.4)	(19.2)	(0.0)			
BAY	0.0019	0.0032	1.6328	-0.0015	0.0000	9.9	0.271	0.0132
	(253.8)	(20.0)	(261.7)	(17.8)	(1.1)			
VOW	0.0045	-0.0020	1.0458	-0.0001	0.0001	9.9	0.273	0.0120
	(30.3)	(1.3)	(230.5)	(0.4)	(0.1)			
ALT	0.0167	0.0000	0.5780	-0.0004	-0.0002	12.7	0.122	0.0200
	(132.0)	(0.0)	(170.6)	(2.6)	(1.8)			
EOA	0.0042	0.0076	1.0663	-0.0021	0.0000	13.0	0.113	0.0085
	(120.8)	(12.9)	(284.5)	(12.7)	(0.6)			
CONT	0.0099	-0.0110	0.8143	0.0015	0.0002	13.2	0.107	0.0253
	(125.6)	(10.7)	(168.0)	(6.3)	(2.0)			
CBK	0.0011	0.0019	2.3990	-0.0014	0.0000	15.8	0.046	0.0171
	(204.6)	(14.2)	(176.9)	(13.7)	(1.6)			
MAN	0.0067	-0.0096	0.9432	0.0016	0.0003	18.5	0.018	0.0229
	(105.3)	(7.8)	(162.9)	(5.3)	(4.3)			
BAS	0.0042	0.0011	1.1199	-0.0008	0.0000	20.8	0.008	0.0108
	(247.1)	(5.0)	(277.7)	(12.6)	(0.8)			
MEO	0.0099	-0.0086	0.9055	0.0008	0.0000	30.6	0.000	0.0255
	(142.1)	(10.1)	(196.0)	(4.9)	(0.2)			
SCH	0.0075	0.0016	0.8237	-0.0007	0.0000	30.8	0.000	0.0152
	(140.7)	(2.8)	(201.0)	(5.6)	(0.4)			
DPW	0.0018	-0.0005	1.8322	-0.0002	-0.0001	55.3	0.000	0.0182
	(217.3)	(2.3)	(175.4)	(1.8)	(2.7)			
LHA	0.0014	-0.0008	2.3132	-0.0003	0.0001	63.5	0.000	0.0226
	(235.1)	(4.8)	(174.6)	(4.0)	(3.9)			
BMW	0.0038	-0.0017	1.2012	-0.0001	-0.0001	130.5	0.000	0.0131
	(222.2)	(7.1)	(233.5)	(2.2)	(2.7)			
RWE	0.0039	-0.0021	1.2440	-0.0001	0.0001	181.8	0.000	0.0144
	(265.5)	(10.4)	(243.1)	(0.9)	(3.2)			
TKA	0.0019	-0.0011	1.9002	0.0000	0.0000	282.1	0.000	0.0226
	(214.8)	(5.7)	(184.0)	(0.5)	(1.1)			

Table 4: First stage GMM results based on average profit conditions instead of marginal profit conditions. 2×4 quotes from the bid and ask side of the complete book (visible and hidden part) are used to construct average update and average break even conditions. The exponential assumption on the distribution of the trade size is maintained. $\tau = \frac{\alpha \cdot \overline{m}}{\overline{P}}$, where $\overline{m}$ and $\overline{P}$ denote stock specific sample averages of the non-signed trade sizes (number of shares) and the midquotes, respectively. The stocks are sorted by ascending $p-$value of the $J-$statistic.

liquidity variable	correlation	$p-$value
quoted spread (%)	0.8968	$< .0001$
effective spread (%)	0.7738	$< .0001$
realized spread (%)	-0.0772	0.685
BLM	0.9816	$< .0001$

Table 5: Correlation of standardized adverse selection component τ with liquidity indicators. The table reports the cross sectional Spearman rank correlations of the standardized adverse selection component τ with a quoted, effective and realized spread. Buy and sell side book liquidity are measured by computing the ratio of a unit price of a hypothetical buy or sell of 100,000 euros and the best available quote on the respective side. We subtract one and multiply the result by 10000. To obtain stock specific measures we take averages over all order book snapshots. Taking absolute values and averaging over the buy and sell side measure, we obtain the book liquidity measure (BLM) used to compute the correlation.

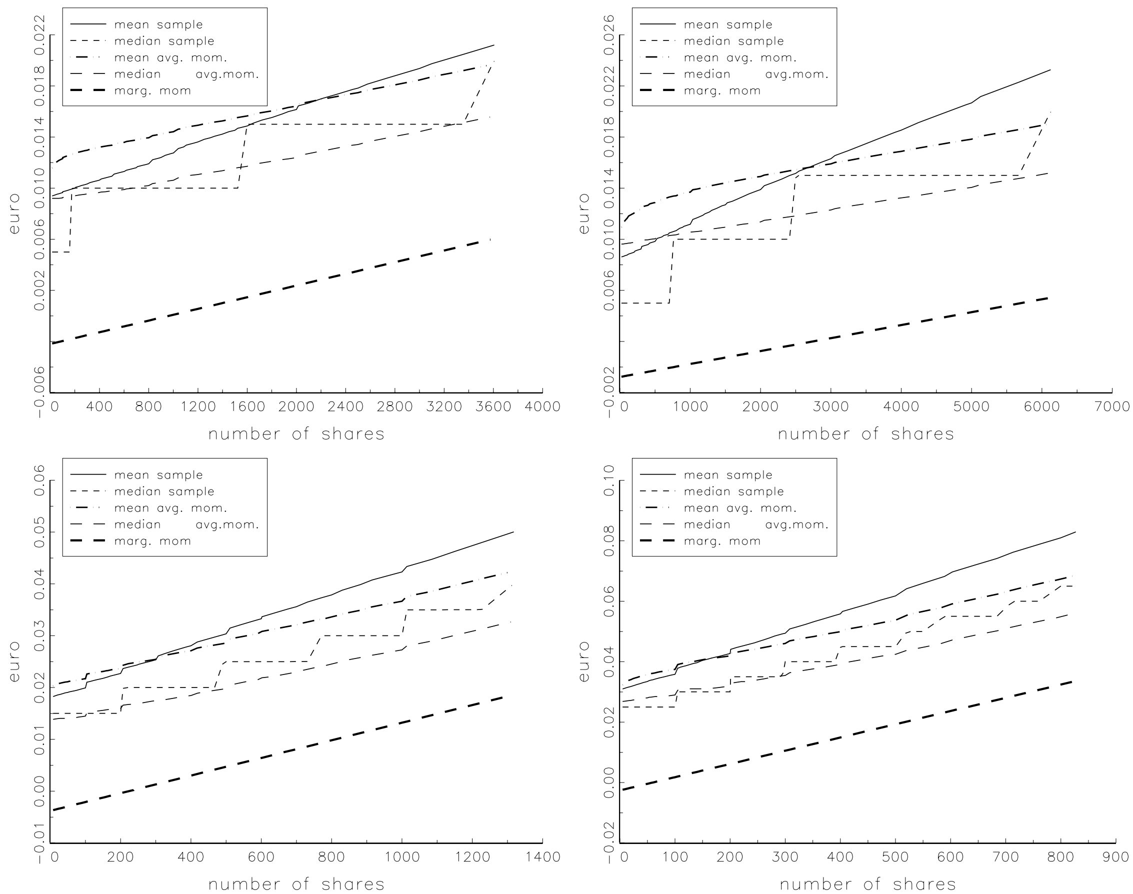

Figure 1: Comparison of implied and observed price schedules The figure depicts means an medians of implied and observed bid side price schedules of four selected stocks. In each figure the values on the horizontal axis show trade volumes (number of shares) up to the 0.9 quantile of the respective stock. The vertical axis show the per share price decrease that a sell trade of a given volume would incur if it were executed against the current book. The solid line depicts sample means and the short dashed lines sample medians computed by using all order book snapshots during the three month period. The bold long-dashed lines depict the mean slope implied by the estimation results reported in table 2 (baseline model that uses marginal break even and update conditions). The dash-dot lines and the long-dashed lines are the mean and the median of the book slope as implied by the estimation results reported in table 4 (revised specification which uses average break even and update restrictions). The stock in the left upper panel is Daimler Chrysler (DCX, from the largest trade volume quartile), the stock in the right upper panel is Bay. Hypo Vereinsbank (HVM, second volume quartile), the stock in the left lower panel is Altana (ALT, third volume quartile) and the stock in the right lower panel is Addidas (ADS, fourth volume quartile).

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