

IPO Underpricing and After-Market Liquidity

Andrew Ellul

Indiana University

Marco Pagano

Università di Napoli Federico II, CSEF and CEPR

The underpricing of initial public offerings (IPOs) is generally explained with asymmetric information and risk. We complement these traditional explanations with a new theory where investors worry also about the after-market illiquidity that may result from asymmetric information after the IPO. The less liquid the aftermarket is expected to be, and the less predictable its liquidity, the larger will be the IPO underpricing. Our model blends such liquidity concerns with adverse selection and risk as motives for underpricing. The model's predictions are supported by evidence for 337 British IPOs effected between 1998 and 2000. Using various measures of liquidity, we find that expected after-market liquidity and liquidity risk are important determinants of IPO underpricing.

The underpricing of the shares sold through initial public offerings (IPOs) is generally explained in the literature with asymmetric information about the security's value and with its fundamental risk. For the IPO to attract sufficient interest, the issuer must leave enough "money on the table" to compensate investors for the uncertainty about the security's value. However, until now the literature has largely disregarded how after-market liquidity may impact on the IPO underpricing. This is a striking omission in view of the established evidence that the returns of seasoned securities include a liquidity premium. One would expect such premium to be paid also by stocks in the process of being floated. Moreover, at the IPO stage, investors do not know precisely how liquid the aftermarket will be. This

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suggests that they will not only care about expected liquidity but also about the uncertainty about it, that is, about liquidity risk.

Our article fills this gap. It complements traditional explanations with theory and evidence showing that after-market liquidity is an important determinant of IPO underpricing. We provide a model showing that an IPO that is expected to be more illiquid and to have higher liquidity risk should feature higher underpricing. We model after-market illiquidity as stemming from the asymmetric information that persists after the IPO stage. Equilibrium stock returns must compensate investors for the losses expected from trading with better informed investors and for the associated risk. In the model, there are two types of private information: a signal that becomes public as soon as shares start trading after the IPO and *some residual private information* that is disclosed at some later date. The first type of private information creates the standard adverse selection problem at the IPO stage while the second determines an adverse selection problem in the aftermarket and is reflected in the bid-ask spread. IPO underpricing will impound also the costs caused by the latter to the extent that some investors expect to liquidate their shares in the aftermarket. One example of these investors are the so-called flippers, who buy the stock at the IPO with a view of selling it immediately after. Such investors will require compensation for the trading cost that they expect to incur, as well as for the associated uncertainty, just as they would for a random transaction tax. The correlation between IPO underpricing and after-market liquidity should therefore be stronger in markets where many initial investors are flippers.

The amount of private information that remains undisclosed after the IPO depends partly on how much information is released at the IPO stage, which is in turn related to the type of IPO mechanism used. Busaba and Chang (2002) show that the bookbuilding process elicits much information from informed traders at the IPO stage by promising larger allocation of valuable stocks to investors who truthfully reveal their information and therefore reduces the impact that such informed traders have in the after-market trading. In contrast, the fixed-price method, that does not elicit such private information at the IPO stage, enables informed traders to use such information in the aftermarket at the expense of the uninformed. The comparatively high adverse selection problems associated with the fixed-price method will spill over from the IPO stage to the aftermarket. This in turn means that liquidity will be relatively more important for IPOs carried out through a fixed-price method than through bookbuilding. This suggests that the empirical analysis must control for the IPO mechanism.

Our model nests the predictions about the effects of after-market liquidity on IPO underpricing with those of traditional models. We test for the presence of these liquidity effects on IPO underpricing, controlling

for the variables suggested by other theories of IPOs. Our sample includes all the companies that went public on the London Stock Exchange (LSE) between June 1998 and December 2000.

We rely on British data because they are uniquely suited for a test of our hypothesis. First, unlike US markets, the London aftermarket does not feature pervasive underwriter stabilization. British investment banks, being more specialized than their US counterparts, seldom have market-making capabilities beside advisory and sponsoring skills (Ljungqvist 2002). In contrast, US IPOs feature pervasive underwriter stabilization where the lead underwriter always becomes the most active dealer in the issue (Aggarwal 2000; Ellis, Michaely, and O'Hara 2000a). Stabilization can artificially enhance liquidity, generating a spurious relationship between underpricing and aftermarket liquidity. Furthermore, underwriter stabilization *per se* could account for IPO underpricing, by reducing the occurrence of initial negative returns (Ruud 1993).

Second, British IPOs are mostly done through the fixed-price method: this, as just argued, should make the correlation between after-market liquidity and IPO underpricing stronger than in a setting where book-building is prevalent such as in the United States.

Third, our tests require accurate measurement of the bid-ask spread and of its intraday variation. The LSE high-frequency data are more suited to this purpose than US publicly available data, in that they precisely identify the direction of trades occurring in the aftermarket. In contrast, in high-frequency data for US stocks (such as the Trade and Quote database) the direction of trades can only be inferred by using algorithms that are known to introduce errors in the measurement of liquidity. Existing literature (Finucane 2000; Ellis, Michaely, and O'Hara 2000b) shows that such algorithms have only limited success in classifying aftermarket trades (especially those executed within the best quotes) leading to biased estimates of effective spreads especially when high volumes are transacted. Such problems are not encountered in the LSE data set.

In line with our model and previous microstructure studies, we focus on measures of liquidity variables that are related to asymmetric information in the trading process: the probability of informed trading (PIN) proposed by Easley et al. (1996) and the adverse selection component of the spread. As a robustness check, we also use the effective bid-ask spread itself. Our main empirical challenge is to estimate the market's expectation of after-market liquidity and of its variability, conditioning on information known at the time of the IPO. We use various methods to tackle this issue.

Consistent with our hypotheses, we find that IPO underpricing is higher for shares featuring lower expected liquidity and higher liquidity risk. The effects of liquidity variables are found to be robust to the

inclusion of the other factors traditionally used to explain IPO underpricing, that is, variables capturing asymmetric information (such as venture capitalist presence, underwriter reputation, number and proceeds of recent IPOs and insiders' options holdings), fundamental risk (such as age of firm, total assets and standard deviation of the after-market mid-quote). The effect of liquidity is also robust to the use of alternative econometric methodologies.

To gain perspective, it is useful to set our contribution against the background of the literature. Many models explain IPO underpricing with some form of information asymmetry about the true value of the IPO shares. In Baron (1982), the issuer knows less about the true value of the company than the investment bank entrusted with the sale, whereas in Benveniste and Spindt (1989) the issuing firms elicit information from investors through their bank's bookbuilding effort. In Rock (1986), the information asymmetry is among potential IPO investors: some are "informed" and others "uninformed," generating a winners' curse problem. The informational asymmetry may also induce investors to rely on other buyers' behavior in placing their bids, leading to an informational cascade. This happens in Welch (1992), where issuers underprice IPO shares to attract some potential investors in the IPO, whose bids will in turn attract other investors.

Little attention has been instead devoted to the link between secondary market liquidity and IPO underpricing. The only exception is the study by Booth and Chua (1996), who suggest that IPO underpricing aims to elicit the interest of a target number of potential investors. They assume that enlarging the pool of dispersed shareholders raises the valuation of the firm, by creating liquidity in the aftermarket, but requires attracting investors with higher information collection costs. The optimal price will weigh the liquidity benefit of added investor participation against its cost. Our article turns this argument on its head. Because different IPO shares feature different after-market liquidity, the IPO underpricing required to attract uninformed investors differs accordingly. The causality runs from aftermarket liquidity to IPO underpricing, contrary to Booth and Chua's logic. Also the predicted sign of the correlation between the two variables is opposite: higher underpricing should lead to greater liquidity according to Booth and Chua (1996) while greater liquidity calls for lower underpricing in our model. Finally, a distinctive prediction of our model is that underpricing should reflect also liquidity risk.

So far, the relationship between returns and liquidity has been analyzed mainly with reference to seasoned securities. Many studies argue that illiquid securities provide investors with a higher expected return to compensate them for the larger trading costs they have to bear. The first paper to model and test this relationship is Amihud and Mendelson's (1986).

Other studies find a significant cross-sectional association between liquidity (as measured by the tightness of the bid-ask spread or trading volume) and asset returns, controlling for risk: among these, Brennan and Subrahmanyam (1996); Eleswarapu (1997); Datar, Naik, and Radcliffe (1998); and Chordia, Roll, and Subrahmanyam (2000). More recently, some studies have investigated also the relationship between liquidity risk and stock returns: while Chordia, Subrahmanyam, and Anshuman (2001) find a negative relationship between returns and the variability of trading volume, Pástor and Stambaugh (2003) document a positive cross-sectional relationship between systematic liquidity risk and stock returns. Butler, Grullon, and Weston (2005) examine seasoned equity issues and find that firms with more liquid shares pay lower investment banking fees and therefore raise capital at more advantageous terms. Closer to the main idea of our model, Easley, Hvidkjaer, and O'Hara (2002) find that information risk, as measured by the probability of trading with informed traders, is a risk factor that is priced by the market.

Liquidity affects also the returns of fixed-income securities, according to several studies.¹ Among these, the closest paper to ours is by Goldreich, Hanke, and Nath (2005), who investigate the impact of *expected* liquidity on current securities' prices. They analyze the prices of Treasury securities as their liquidity changes predictably, in the transition from on-the-run to the less liquid off-the-run status. They show that more liquid securities command higher prices, but this liquidity premium depends on the expected future liquidity over their remaining lifetime rather than on their current liquidity.

Our article can be seen as extending the insights from this literature to the primary equity market. If seasoned securities pay a liquidity premium, it is reasonable to expect also stocks on the primary market to pay such premium—especially if the market for IPO shares is much less liquid than that for seasoned issues, as we find empirically. Moreover, for IPO shares liquidity is also an additional source of uncertainty, more than for seasoned securities. IPO investors do not know yet how liquid the aftermarket will be and therefore will want to be compensated *also* for liquidity risk.

This article is organized as follows. Section 1 presents a model nesting the impact of liquidity on IPO underpricing with more traditional theories and providing the basis for our empirical tests. Section 2 reviews the

¹ Amihud and Mendelson (1991) show that the yield to maturity of treasury notes with six months or less to maturity exceeds the yield to maturity on the more liquid treasury bills. Other studies on US public debt securities by Warga (1992), Daves and Ehrhardt (1993), Kamara (1994), and Krishnamurthy (2002) confirm these findings. However, using more recent data, Strebulaev (2001) finds that the yield spread between bills and matched notes is much smaller than previously found, especially when bills are on-the-run. Some studies apply the same idea by comparing securities with identical cash flows but different trading opportunities. Silber (1991) compares stocks with different trading restrictions. Dimson and Hanke (2001) examine equity-linked bonds with the same cash flows as an investment in an equity index and find that they sell at a discount relative to their underlying value, which can be attributed to their low liquidity.

data and presents the measures of liquidity used in the estimation. Section 3 presents the empirical methodology and illustrates the results. Section 4 concludes.

1. The Model

In this section, we develop a simple theoretical model to explain the relationship between after-market liquidity and IPO underpricing and derive the hypotheses to be tested. In this model, there are three stages: at $t = 0$, the IPO occurs; at $t = 1$, the company's shares are traded on the aftermarket, and at $t = 2$, the shares are liquidated (or can be traded) at their fundamental value. The time line in Figure 1 illustrates these three stages and describes the information and actions of market participants at each stage.

The model captures the presence and interaction of two distinct adverse selection problems: that affecting the primary market [as in the classic model of IPO underpricing by Rock (1986)] and that determining secondary market liquidity [as in the equally classic model by Glosten and Milgrom (1985)]. In the model's baseline version, developed assuming risk neutrality, IPO underpricing is determined not only by adverse selection in the IPO process, but also by the magnitude of the spread in the aftermarket. When uninformed investors are assumed to be risk averse, IPO underpricing is also affected by fundamental risk, by its interaction with adverse selection in the IPO and with the after-market spread, and by a quadratic term in the bid-ask spread. Finally, we extend the model to encompass also liquidity risk, assuming that at the IPO stage

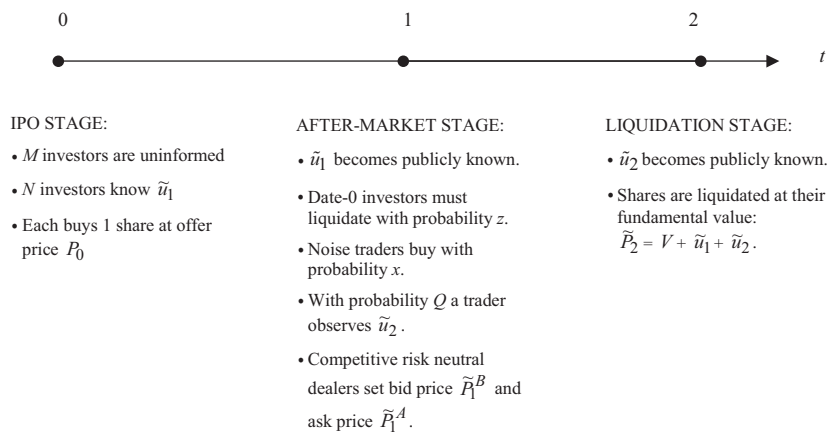


Figure 1
Time line of the model.

investors do not know the precise level of the after-market bid-ask spread. In this extended version, IPO underpricing is also increasing in liquidity risk: investors require compensation not only for the expected level of trading costs in the aftermarket, but also for their variability.

Before turning to the model, it is worth noting that its results would be qualitatively unchanged if the bid-ask spread resulted from the inventory holding costs or order processing costs of dealers, rather than information asymmetries. Our modeling focus on the latter is dictated by the idea that information asymmetries are likely to be particularly large in trading after the IPO, when much learning about fundamentals is still to occur and the risk of future private information is largest. This idea is consistent with the evolution of both the PIN measure and the adverse selection component of the spread, which both decline steadily in the first weeks after the IPO, as will be seen in Section 2.

1.1 Information structure

The company's fundamental value is $\tilde{V} = V + \tilde{u}_1 + \tilde{u}_2$, where V is a positive constant and $\tilde{u}_1$ and $\tilde{u}_2$ are independently distributed random variables that represent "news" publicly disclosed at stages 1 and 2, respectively.² The variable $\tilde{u}_1$ equals $-\eta$ or η with probability 1/2 each: if $\tilde{u}_1 = \eta$ the company is disclosed to be of high quality in after-market trading, whereas if $\tilde{u}_1 = -\eta$ the company is revealed to be of low quality. Similarly, $\tilde{u}_2$ equals $-\varepsilon$ or ε with probability 1/2 implying that in after-market trading there is still some residual uncertainty about the final value of the company. Therefore, the expected value of a share based only on public information is V at $t = 0$, $V + \tilde{u}_1$ at $t = 1$, and $V + \tilde{u}_1 + \tilde{u}_2$ at $t = 2$.

Some investors base their actions not only on public, but also on private information, at the IPO stage as well as in after-market trading. At $t = 0$, the investors who can buy the company's shares are of two types: while M of them are uninformed, N have advance knowledge of the realized value of $\tilde{u}_1$, that is, know the company's quality. Similarly, at $t = 1$, with probability Q a trader has advance information about the realized value of $\tilde{u}_2$, that is, knows the company's final value and conditions his orders on such information. The sequence of events and the evolution of the information structure are shown in Figure 1.

² Investors can become informed at $t = 1$ irrespective of whether they bought shares at the IPO stage or not, but we do not rule out that private information may reside with the same people both at the IPO stage and at the after-market stage. In this case, however, we require that the two signals that they observe at these two moments be uncorrelated and short-lived pieces of information, in that each of them becomes public in the subsequent period. If instead the two signals were correlated and contained long-lived information, informed investors would have a nontrivial choice between exploiting their private information at the IPO stage and doing so in after-market trading: Busaba and Chang (2002) explore this setting.

1.2 Primary and secondary market structure

The primary market is modeled as in Rock's model. The company sells an exogenous number of S shares in the IPO. It maximizes the IPO sale revenue $P_0 S$ by choosing the highest offer price P_0 consistent with selling all S shares. If possible, the S shares are sold by filling all the bids made at the preset price P_0 ; otherwise, they are allocated through a lottery that gives the same probability of receiving one share to each bidder. The uninformed investors are wealth constrained: each of them can buy at most one share with his initial wealth (plus any credit he can obtain), at the equilibrium price P_0 . Investors cannot buy fractional values of a share in the IPO.

Uninformed investors are sufficiently numerous that they can buy all the shares on sale if they all bid ($M > S$) while informed investors cannot if they bid for one share each ($S > N$). Because informed investors must bid for one unit each to avoid giving themselves away, the IPO price must be chosen so as to attract also bids from uninformed investors.

The secondary market that opens at $t = 1$ is operated by dealers. Apart from its analytical convenience, this assumption is attuned to our data, which refer to a dealer market. Dealers are assumed to be risk neutral and perfectly competitive, so that their expected profits are zero. There are no restrictions on short sales. Each order is to be filled at the quoted price for one unit: at the time of accepting a trade, dealers do not know whether another buy or sell order has also arrived on the market. Hence the ask price at which they are willing to offer one unit is the expected value of the security, given a buy order by a trader of unknown identity. Symmetrically, the bid price is the expected value of the security, given a sell order by a trader of unknown identity.

1.3 Investors' preferences and liquidity needs

We assume all investors to be risk neutral—an assumption that we shall relax later. In addition, all investors have potential liquidity needs: anyone who buys shares at $t = 0$ has to liquidate them with probability z at $t = 1$ and therefore holds them until $t = 2$ only with probability $1 - z$. For notational simplicity (and with no loss of generality), we assume that each potential liquidity trader is matched with one dealer, so that z is also the probability with which a dealer will receive a liquidity-motivated sell order in the aftermarket. At $t = 1$ each dealer receives orders from liquidity-motivated buyers with probability x . We do not model the process that generates these buy orders, but this is not relevant for our results about IPO underpricing, because these are affected only by the sell side of aftermarket. (In fact, IPO underpricing would be unaffected even if dealers were to receive only sell orders in the aftermarket.)

To decide whether bidding for a share in the IPO, each investor will consider if the expected value of the share to him, conditional on the information that he has, exceeds the IPO offer price P_0 . To compute this expected value, the investor will consider that with probability z he will have

to liquidate his shareholdings at the bid price $\tilde{P}_1$ that the dealer will post at $t = 1$. With probability $1 - z$, instead, he will be able to hold them until $t = 2$ and then sell them at the price $\tilde{P}_2$. Investor j , where $j = \{i, u\}$ indexes informed and uninformed investors will bid price P_0 for a share in the IPO if

$$zE(\tilde{P}_1^B | \Omega_0^j) + (1 - z)E(\tilde{P}_2 | \Omega_0^j) \geq P_0, \quad (1)$$

$\tilde{P}_1^B$ being the price at which the investor can resell the share at $t = 1$ (the dealer's bid price) and Ω_0^j being the investor's information set at $t = 0$, so that $\Omega_0^j = \{\Omega_0^u, \tilde{u}_1\}$. In computing the expectations in Equation (1), uninformed investors have to take into account the probabilities that by bidding P_0 they get high- or low-quality shares. We shall denote these probabilities by π_u and $1 - \pi_u$, respectively.

1.4 Market equilibrium with risk-neutral investors

The equilibrium is found by backward induction. Because at $t = 2$ all information is public, the final price of a share equals its fundamental value: $\tilde{P}_2 = \tilde{V}$.

At $t = 1$, the quality of the company sold at the IPO is public knowledge: $\tilde{u}_1$ is known by all investors. However, some uncertainty remains for dealers and most investors, $\tilde{u}_2$ being known at most to an insider. The insider observes $\tilde{u}_2$ with probability Q , and thus sees $\tilde{u}_2 = \varepsilon$ or $\tilde{u}_2 = -\varepsilon$ with probability $Q/2 \equiv q$ each. To maximize the expected gain from his trades, the insider will place a buy order if $E(\tilde{V} | \tilde{u}_2) - P_1^A = \tilde{V} - P_1^A > 0$ and a sell order if $E(\tilde{V} | \tilde{u}_2) - P_1^B = \tilde{V} - P_1^B < 0$. To avoid revealing his identity, the insider's order size will be equal to that of liquidity traders' orders.

Recalling that at $t = 0$ each investor bought at most one share, liquidity traders sell a unit at $t = 1$, and therefore also the insider sells at most one unit if $\tilde{V} - P_1^B < 0$. Because a liquidity trader sells a unit with probability z , the conditional probability that a sell order comes from the liquidity trader is $z/(q + z)$, and the conditional probability that it comes from the informed trader is $q/(q + z)$. The bid price set by the competitive dealers is the expectation of the share's value, conditional on the signal $\tilde{u}_1$ (that by now is public information) and on receiving a sell order:

$$\begin{aligned} \tilde{P}_1^B &= E(\tilde{V} | \tilde{u}_1, \text{sell}) = \frac{q}{q + z}(V + \tilde{u}_1 - \varepsilon) + \frac{z}{q + z}(V + \tilde{u}_1) \\ &= V + \tilde{u}_1 - \frac{q}{q + z}\varepsilon. \end{aligned} \quad (2)$$

Similarly, recalling that a liquidity trader buys a unit with probability x , the ask price is

$$\begin{aligned} \tilde{P}_1^A &= E(\tilde{V} | \tilde{u}_1, \text{buy}) = \frac{q}{q + x}(V + \tilde{u}_1 + \varepsilon) + \frac{x}{q + x}(V + \tilde{u}_1) \\ &= V + \tilde{u}_1 + \frac{q}{q + x}\varepsilon. \end{aligned} \quad (3)$$

The bid-ask spread therefore is

$$S \equiv \tilde{P}_1^A - \tilde{P}_1^B = \underbrace{\frac{q}{q+x}}_{S_A} \varepsilon + \underbrace{\frac{q}{q+z}}_{S_B} \varepsilon, \quad (4)$$

The terms S_A and S_B are the spread's bid-side and ask-side portions, respectively, that is, the trading costs that an uninformed buyer or seller pays relative to his estimate $V + \tilde{u}_1$ of the share value. The spread S increases in the probability of the insider's orders (q) and decreases in the probability of liquidity buy (x) and sell orders (z). Notice that the spread's bid-side portion S_B increases in q and decreases in z but is unaffected by x : the liquidity faced by a seller is unaffected by the behavior of liquidity buyers.

Now let us turn to the equilibrium at $t = 0$. From Equation (1), we know that investors informed about $\tilde{u}_1$ bid for shares at the IPO only if

$$zE(\tilde{P}_1|\Omega_0^i) + (1-z)E(\tilde{P}_2|\Omega_0^i) \geq P_0. \quad (5)$$

So these investors' bids will impound their private information $\tilde{u}_1$ only if

$$zE(\tilde{P}_1^B|\tilde{u}_1 = \eta) + (1-z)E(\tilde{P}_2|\tilde{u}_1 = \eta) \geq P_0 > zE(\tilde{P}_1^B|\tilde{u}_1 = -\eta) + (1-z)E(\tilde{P}_2|\tilde{u}_1 = -\eta),$$

which, using Equation (2) and recalling that $\tilde{P}_2 = V + \tilde{u}_1 + \tilde{u}_2$, can be rewritten as

$$V + \eta - z \frac{q}{q+z} \varepsilon \geq P_0 > V - \eta - z \frac{q}{q+z} \varepsilon. \quad (6)$$

Condition (6), which will be shown to hold in equilibrium, ensures that the informed traders' optimal strategy is to bid only if the company is of good quality ($\tilde{u}_1 = \eta$). Otherwise, they would always bid or never bid irrespective of their private information.

As for uninformed investors, from Equation (1) they will bid if

$$zE(\tilde{P}_1^B|\Omega_0^u) + (1-z)E(\tilde{P}_2|\Omega_0^u) \geq P_0, \quad (7)$$

where, as explained before, expectations are computed using the firm's quality probability distribution conditional on the uninformed bid's success. If π_u denotes the probability that an uninformed investor bidding P_0 gets shares of a high-quality company ($\tilde{u}_1 = \eta$) and $1 - \pi_u$ the probability that he will get shares of a low-quality company ($\tilde{u}_1 = -\eta$), the prices that this investor expects to face in the two subsequent periods are

$$\begin{aligned} E(\tilde{P}_1^B|\Omega_0^u, P_0) &= \pi_u \left(V + \eta - \frac{q}{q+z} \varepsilon \right) + (1 - \pi_u) \left(V - \eta - \frac{q}{q+z} \varepsilon \right) \\ &= V - \frac{q}{q+z} \varepsilon - (1 - 2\pi_u)\eta \end{aligned} \quad (8)$$

and

$$E(\tilde{P}_2 | \Omega_0^\mu, P_0) = \pi_u(V + \eta) + (1 - \pi_u)(V - \eta) = V - (1 - 2\pi_u)\eta. \quad (9)$$

From the last three equations, the condition ensuring that uninformed investors participate in the IPO can be rewritten as

$$V - (1 - 2\pi_u)\eta - z \frac{q}{q+z} \varepsilon \geq P_0. \quad (10)$$

The company will set the offer price at the highest level consistent with participation by the uninformed investors in the IPO, that is, will choose P_0 so that condition (10) holds with equality. This implies also that condition (6) concerning informed investors is satisfied. Therefore, if the company is of high quality, both types of investors bid, and uninformed investors get shares with probability $\lambda = M/(M + N)$. If the company is of low quality, only uninformed investors bid, and get shares with probability 1. Since the unconditional probability of the firm being of high quality is 1/2, the probability that the company is of high quality conditional on uninformed investors being allocated shares is

$$\pi_u = \frac{\lambda/2}{\lambda/2 + 1/2} = \frac{\lambda}{1 + \lambda}. \quad (11)$$

Using this result in condition (10) taken with equality, we get the equilibrium offer price:

$$P_0 = V - \frac{1 - \lambda}{1 + \lambda} \eta - z \frac{q}{q+z} \varepsilon = V - \frac{1 - \lambda}{1 + \lambda} \eta - z S_B, \quad (12)$$

where in the second step we used the fact that the spread's bid-side portion $S_B = [q/(q+z)]\varepsilon$. Therefore, the offer price is negatively related to the probability of informed sales in the aftermarket: the ratio $q/(q+z)$ is the direct counterpart of the PIN measure proposed by Easley et al. (1996).

This immediately yields the following expression for average IPO underpricing:

$$E(\tilde{P}_1) - P_0 = \frac{1 - \lambda}{1 + \lambda} \eta + z S_B, \quad (13)$$

where $E(\tilde{P}_1)$ is the average transaction price in the aftermarket.³ Notice that, as percentage of the offer price, IPO underpricing is a convex

³ To obtain Equation (13), we have used the fact that $E(\tilde{P}_1) = V$. To see this, notice that in computing $E(\tilde{P}_1)$ each of the prices quoted by the dealer is weighted by the frequencies of the corresponding orders. The dealer receives a buy order with probability $(q+x)/(2q+x+z)$ so that the transaction price is the bid price $\tilde{P}_1^B$ in Equation (2). He receives a sell order with probability $(q+z)/(2q+x+z)$ so that the transaction price is the ask price $\tilde{P}_1^A$ in Equation (3). As a result, the average transaction price conditional on a given realization of $\tilde{u}_1$ is $E(\tilde{P}_1 | \tilde{u}_1) = V + \tilde{u}_1$. Since the expected value of $\tilde{u}_1$ is zero, the unconditional average of the after-market price $E(\tilde{P}_1) = V$.

function of expression (13). Denoting the latter by A , it is easy to see that (one plus) percentage underpricing is

$$\frac{E(\tilde{P}_1)}{P_0} = \frac{V}{V - A}. \quad (13')$$

Equation (13) has a simple interpretation. In equilibrium, IPO underpricing compensates uninformed investors not only for the adverse selection costs borne at the IPO stage (the first term), but also for the expected trading costs that they will bear by liquidating their shares in the after-market (the second term). As in Rock's model, the adverse selection cost at the IPO stage is decreasing in the fraction of uninformed investors, λ , and increasing in the standard deviation of the signal they observe, η , which measures their informational advantage. The expected trading costs are increasing both in the probability of reselling shares in the aftermarket, z , and in the bid-side portion of the spread, S^B , which in this model reflects the severity of the adverse selection problem in secondary market trading.

We now generalize the model to the case of risk-averse investors, who require IPO underpricing to reward them not only for illiquidity, but also for risk of IPO shares. We will start with a situation where risk is about the stock fundamentals (Section 1.5), and then consider a setting where also the degree of after-market liquidity is unknown, and therefore creates an additional source of risk, that is, liquidity risk (Section 1.6).⁴

1.5 Market equilibrium with risk-averse investors

Suppose that the investors with no private information at the IPO maximize expected utility $E[U(\tilde{W})]$, where $U(\cdot)$ is concave and twice differentiable in final wealth W . For simplicity, other market participants and dealers are still assumed risk neutral. Thus, only the condition for the participation of uninformed investors now changes from Equation (7) into

$$zE[U(\tilde{P}_1^B)|\Omega_1^u] + (1 - z)E[U(\tilde{P}_2)|\Omega_0^u] \geq P_0, \quad (14)$$

⁴ Besides enriching the predictions about IPO underpricing, introducing risk aversion in the model carries other interesting implications. For instance, it suggests that firms may want to increase after-market liquidity (by subsidizing the bid price), which is never worthwhile under risk neutrality. If investors are risk neutral and if all after-market sellers bought shares at the IPO stage, the expected benefit from the additional liquidity and the corresponding subsidy paid by the firm offset each other, so that the IPO price is unaffected. If after-market sellers include also investors who did not buy shares at the IPO stage, then part of the expected subsidy would leak outside the pool of the IPO investors and the firm's after-market intervention would lower the IPO price: the latter would still discount the entire cost of the subsidy but not its entire benefit. If investors are risk averse, instead, subsidizing after-market liquidity may increase the IPO price, because it would effectively allow IPO investors to insure against liquidity shocks. (Also in this case, part of the benefit may be dissipated on investors who did not purchase shares at the IPO, so that increasing after-market liquidity is worthwhile only if this "leakage" is not too severe.) Anyway, this possibility does not alter the empirical predictions of the model about the relationship between underpricing and after-market liquidity because the firm will attempt to increase after-market liquidity only when this raises the IPO price.

where, as before, expectations are computed using the probability distribution of the firm's quality conditional on the uninformed bid's success.

As in the previous section, in equilibrium the offer price makes uninformed investors just indifferent between bidding and not bidding for the company's shares: it is the value of P_0 that makes condition (14) hold with equality. As shown in the appendix through steps similar to those used in the previous section, the equilibrium offer price P_0 solves

$$U(P_0) \approx U(V) - U'(V) \left(\frac{1-\lambda}{1+\lambda} \eta + zS_B \right) + \frac{U''(V)}{2} \left[\eta^2 + (1-z)\varepsilon^2 + z \left(S_B^2 + 2 \frac{1-\lambda}{1+\lambda} \eta S_B \right) \right].$$

Given the properties of $U(\cdot)$, one can write $U(V) - U(P_0) = f(V - P_0)$ where $f(\cdot)$ is an increasing function. Using this fact and recalling that $E(\tilde{P}_1) = V$, IPO underpricing can be written as $E(\tilde{P}_1) - P_0 \approx h\{U[E(\tilde{P}_1)] - U(P_0)\}$, where $h(\cdot) = f^{-1}(\cdot)$, which is an increasing function. Using this result in the last equation yields the following expression for average IPO underpricing:

$$E(\tilde{P}_1) - P_0 \approx h \left\{ \alpha \left(\frac{1-\lambda}{1+\lambda} \eta + zS_B \right) + \frac{\alpha\rho}{2} \left[\eta^2 + (1-z)\varepsilon^2 + z \left(S_B^2 + 2 \frac{1-\lambda}{1+\lambda} \eta S_B \right) \right] \right\}, \quad (15)$$

where $\alpha \equiv U'(V)$ and ρ is the coefficient of absolute risk aversion.⁵

Expression (15) nests various subcases:

- (1) As expected, it reduces to Equation (13) in the case of risk neutrality (where $V - P_0 = (1/\alpha)[U(V) - U(P_0)]$ and $\rho = 0$).
- (2) The equation yields a purely risk-based model of IPO underpricing if investors are risk averse ($\rho > 0$) but adverse selection problems are absent both at the IPO stage ($\lambda = 1$) and in the aftermarket ($q = 0$, implying $S_B = 0$). In this case, underpricing is $E(\tilde{P}_1) - P_0 \approx h\{(\alpha\rho/2)[\eta^2 + (1-z)\varepsilon^2]\}$, that is, it compensates investors only for fundamental risk (the variance of fundamentals decreases in z , because investors do not bear the risk deriving from the shock $\tilde{u}_2$ if they liquidate at $t = 1$).
- (3) With adverse selection at the IPO stage ($\lambda < 1$), but not in the aftermarket ($S_B = 0$), we have the additional term $\alpha[(1-\lambda)/(1+\lambda)]\eta$. Instead, the risk-premium component (the term in square brackets multiplied by ρ) stays unchanged. This shows that in the context of a Rock-style model there is no

⁵ Expression (15) is obtained from a second-order Taylor-series approximation explained in the Appendix.

interaction between the adverse selection and the risk premium components of IPO underpricing.

- (4) If there is also adverse selection in the aftermarket, that is, with a positive bid-ask spread ($S_B > 0$), underpricing is higher for three reasons. First, as in the risk-neutrality case, there is the direct disutility because of the expected trading cost ($\alpha z S_B$). Second, the bid-ask spread increases the risk to be borne by the investor ($\alpha \rho z S_B^2/2$): the interaction between informed traders and dealers impounds advance information about $\tilde{u}_2$ in the aftermarket price and thereby increases the risk borne in case of early liquidation of the shares. The illiquidity of the aftermarket exacerbates risk and increases the risk premium component of IPO underpricing. Thirdly, Equation (15) shows that underpricing also includes an interaction term between risk, adverse selection at the IPO stage, and after-market illiquidity ($\alpha \rho z [(1 - \lambda)/(1 + \lambda)] \eta S_B$).

Since IPO underpricing is generally expressed as a percent of the offer price, it is worth noting that, if Equation (15) is rewritten as $E(\tilde{P}_1) - P_0 \approx h(\alpha A)$, also the percentage IPO underpricing is an increasing function of A :

$$\frac{E(\tilde{P}_1)}{P_0} \approx \frac{V}{V - h(\alpha A)}. \quad (15')$$

For instance, if utility is logarithmic, the model predicts that $E(\tilde{P}_1)/P_0 = \exp(A/V)$, which can be rewritten as

$$\log\left(\frac{E(\tilde{P}_1)}{P_0}\right) = \frac{1 - \lambda}{1 + \lambda} \eta + z S_B + \frac{\rho}{2} \left[\eta^2 + (1 - z) \varepsilon^2 + z \left(S_B^2 + 2 \frac{1 - \lambda}{1 + \lambda} \eta S_B \right) \right]. \quad (15'')$$

Therefore, if underpricing is measured as $\log(E(\tilde{P}_1)/P_0)$, it should be a linear-quadratic function of the after-market half-spread S_B , with a linear coefficient proportional to the frequency of liquidity sales z and a quadratic coefficient $\rho z/2$. For power utility functions $U(x) = x^\gamma$, with $\gamma \leq 1$, the model predicts that $E(\tilde{P}_1)/P_0 = [V/(V - \gamma A)]^{1/\gamma}$, which reduces to expression (13') for the risk-neutral case ($\gamma = 1$).

1.6 Market equilibrium with uncertain liquidity

So far, investors were assumed to anticipate perfectly the degree of secondary market liquidity, as summarized by the bid-ask spread S_B . But this may not be a reasonable assumption for shares that are not

traded yet: when the offer price is set, investors may not know how liquid the secondary market will be.

The uncertainty about liquidity can be captured by assuming that there can be two liquidity regimes, characterized by a different incidence of insider trading and therefore by a different bid-ask spread. More precisely, let the fraction of insider traders be a random variable $\tilde{q}$ that takes a low value q_L or a high value q_H with equal probability. Accordingly, the (bid-side portion of the) spread becomes itself a random variable:

$$\tilde{S} = \frac{\tilde{q}}{\tilde{q} + z} \varepsilon \quad (16)$$

The distribution of $\tilde{q}$ (and therefore that of $\tilde{S}$) is independent of those of $\tilde{u}_1$ and $\tilde{u}_2$. With this change to the model, there are four possible states on the aftermarket, depending on the quality of the company (high or low: $\tilde{u}_1 = \eta$ or $\tilde{u}_1 = \eta$) and on the liquidity regime (high or low: $\tilde{q} = q_L$ or $\tilde{q} = q_H$), with probability 1/4 each.

As in the previous section, the equilibrium offer price is the value of P_0 that makes the uninformed investors' participation constraint (14) hold with equality. As shown in the Appendix through steps similar to those of the previous section, in equilibrium the average level of IPO underpricing in this expanded model is

$$\begin{aligned} E(\tilde{P}_1) - P_0 \approx & h \left(\alpha \left(\frac{1-\lambda}{1+\lambda} \eta + z E(\tilde{S}_B) \right) + \frac{\alpha \rho}{2} [\eta^2 + (1-z)\varepsilon^2] \right. \\ & \left. + \frac{\alpha \rho}{2} z \left\{ Var(\tilde{S}_B) + [E(\tilde{S}_B)]^2 + 2 \frac{1-\lambda}{1+\lambda} \eta E(\tilde{S}_B) \right\} \right) \end{aligned} \quad (17)$$

This expression differs from its analogue (15) obtained under perfect foresight about liquidity only in two respects. The bid-ask spread S_B is replaced by its expected value $E(\tilde{S}_B)$, and its square S_B^2 by $E(\tilde{S}_B^2) = Var(\tilde{S}_B) + [E(\tilde{S}_B)]^2$. We recover expression (15) as a special case of (16) for $q_H = q_L = q$, where the spread is nonstochastic ($\tilde{S}_B = S_B$).

Therefore, the extended model with uncertain liquidity predicts that IPO underpricing is an increasing function of the expected bid-ask spread $E(\tilde{S}_B)$ and of its variance $Var(\tilde{S}_B)$. The model nests this prediction with those of models based on adverse selection in the IPO—the first term in (17)—and on fundamental risk—the terms in the first square brackets. In keeping with this feature of the model, therefore, our tests for the presence of liquidity effect on underpricing will control for variables designed to capture adverse selection and risk, along the lines of previous empirical studies on this matter.

2. Data Description and Liquidity Measures

2.1 Data description

We analyze all the IPOs undertaken on the LSE from June 1998 to December 2000.⁶ From this sample we eliminate closed-end funds, open-end funds, and investment companies. This leaves us with 337 IPOs, of which 37 went public in 1998, 121 in 1999 and 179 in 2000. Table 1 illustrates the composition of the sample, by size and sector (panel A) and by market (panel B).

Table 1
Composition of the sample

Sector	First size quartile	Second size quartile	Third size quartile	Fourth size quartile	Total
Panel A					
1. Resources	0	0	2	3	5
2. Basic industries	0	1	3	2	6
3. General industries	2	5	3	7	17
4. Cyclical consumer goods	1	6	1	6	14
5. Noncyclical consumer goods	7	7	8	8	30
6. Cyclical services	25	18	34	18	95
7. Noncyclical services	19	4	4	6	33
8. Financials	8	6	10	16	40
9. Information technology	29	30	20	18	97
Age (years)	Main Market	Alternative Investment Market	Total		
Panel B					
Age ≤ 1	3	71	74		
1 < age ≤ 2	6	18	24		
2 < age ≤ 3	9	14	23		
3 < age ≤ 4	14	19	33		
4 < age ≤ 5	10	11	21		
5 < age ≤ 6	7	22	29		
6 < age ≤ 7	5	15	20		
7 < age ≤ 8	6	14	20		
8 < age ≤ 9	3	9	12		
9 < age ≤ 10	6	9	14		
Age > 10	31	35	67		

The table illustrates the composition of the sample, which refers to the 337 initial public offerings (IPOs) carried out between July 1998 and December 2000 on the London Stock Exchange. Panel A shows the breakdown of the sample by sector and size (as measured by total assets). Each cell reports the number of companies in the corresponding sector and size quartile. Panel B shows the breakdown of the sample by age (as measured by years from incorporation to the date of the IPO) and market of listing (Main Market or Alternative Investment Market).

⁶ For the period from July 1996 to June 1998, price and quote data are unavailable from the LSE.

For each company, we collect two types of data: (i) tick-by-tick transaction and quote data provided by the LSE and (ii) company-level data, drawn from IPO prospectuses filed with the Financial Services Authority (FSA), the UK Listing Authority.

The LSE data include for each company (i) date and time of each trade executed in the aftermarket, (ii) quantity transacted in each trade, (iii) transaction price, and (iv) trade direction (buyer or seller originated), from inception of trading up to the end of 2000.

The FSA data concern the terms of the IPO (offer price, IPO mechanism, number of shares issued in the IPO, stabilization agreement with the underwriter, etc.), firm characteristics (age,⁷ sector, sales, assets, leverage, presence of venture capitalists), and ownership and control (shares sold by the initial shareholder, percentage of shares held by private investors after the IPO, changes in stock options held by insiders, etc.). When the prospectus was not available from the FSA, these data were drawn from *Worldscope*.

The companies in our sample list either on the Main Market (MM) or on the Alternative Investment Market (AIM) of the LSE, depending on their accounting records. The two markets have the same trading system (they are both dealer markets with designated market-makers) but list different types of companies. The AIM caters exclusively to small companies with a short track record while the MM lists companies with no less than three years of accounting profits, though this requirement was relaxed in our sample period to accommodate some young, high-growth firms with no earnings. As a result, the companies listed on the MM are generally larger and older than those listed on AIM. As shown by Panel B of Table 1, 91% of the companies under two years from incorporation went public on the AIM. The sector distribution of the two markets is roughly the same. Due to the different listing requirements of the two market segments, companies have little discretion as to the market they will list on, so that their distribution across the two segments can be regarded as largely exogenous.

The design of the IPO sale also differs considerably within our sample. Most small companies go public through a fixed-price auction, where the price is set before the bidding and, in case of overbidding, rationing occurs according to a scheme set in the IPO prospectus. Large companies set their IPO price either through a fixed-price auction or through a book-building process. Underwriters' stabilization is far less widespread in the London market than in the US, and its occurrence is explicitly stated in IPO prospectuses. Our data reveal that some companies listing on the MM enter into a price stabilization agreement with the underwriter, and in this case they generally provide the underwriter with a "green shoe" option.

⁷ The age of the company is computed from the year of incorporation. If the company results from a merger or takeover, its assumed birth date is the year of incorporation of the oldest company.

Table 2 provides descriptive statistics for the IPOs in our sample. The table shows that the typical firm making an IPO operates for more than seven years before the IPO, has total sales of £51.2 millions in the year before the IPO, fixed assets totaling £135.1 millions, and is valued at £174.3 millions at the time of the IPO. Of interest are the changes in the insiders' holdings that occur during the IPO stage. On average, the insiders sell 6.65% of their stake (in the pre-IPO share capital) during the IPO. These sales, together with the amount of new shares issued by the company, on average reduce the insiders' holdings by 26.5% in the post-IPO company. Furthermore, executive and independent directors hold, on average, options worth 2.29% of post-IPO shares.

Table 2
Companies and initial public offering (IPO) characteristics: descriptive statistics

Variable	Mean	Median	Standard deviation	Minimum	Maximum
Company characteristics					
Firm size (sales, £ million)	51.22	1.90	318.18	0	3,800
Firm size (market cap, £ million)	174.27	25.37	673.19	0.17	7,523
Firm age (years)	7.12	5.0	12.72	0.04	154
Fixed assets (£ million)	135.07	1.01	1,757.99	0.0	32,000
Leverage (short-term debt, percent)	49.62	42.10	54.56	0	465.81
Leverage (long-term debt, percent)	69.07	56.25	71.84	0	589.17
IPO characteristics					
Underpricing—first day (%)	47.66	22.80	82.86	−61.20	660.0
Underpricing—first four weeks (%)	29.58	11.36	66.72	−66.00	398.0
Shares offered (in 100,000)	397.00	137.00	1,716.00	5.00	29,500.00
Shares sold by main shareholders (in 100,000)	57.90	0.01	160.0	0	1980.0
Equity issued (%)	31.89	25.10	23.84	1.8	99
Sales by insiders (%)	6.65	0.0	11.47	0	84.00
Directors' options (%)	2.29	1.00	3.14	0	19.46
Venture capitalists' presence	0.47	0	0.50	0	1
Independent directors' presence (%)	45.67	42.86	16.53	0	100

The table shows statistics for the 337 IPOs carried out between June 1998 and December 2000 on the London Stock Exchange. Trading data were supplied by the London Stock Exchange. Data about firm characteristics are drawn from the prospectuses filed with the Financial Services Authority (the UK Listing Authority). All figures are cross-sectional statistics. Firm sales refer to the year preceding the IPO, and firm capitalization refers to the time of the IPO. Firm age is the number of years between the firm's initial incorporation and the time of the IPO. In case of mergers and takeovers, the date of incorporation refers to the oldest firm. Fixed assets are the firms' fixed assets at the time of the IPO. Leverage is the cross-sectional average of long-term debt to assets held by the firm at the time of the IPO. Underpricing—first day is the percentage difference between the closing mid-price on the first day of trading and the offer price. Underpricing—first 4 weeks is the same measure with reference to the 20th day of trading. Shares offered is the number of shares placed on the market in the IPO. Shares sold by main shareholders is the number of shares offered by the major shareholders (defined as the shareholders holding 3% or more of the share capital at the time of the IPO). Equity issued is the *new* share capital placed by the company in the IPO expressed as a percentage of the post-IPO capital. Sales by insiders is the amount of shares sold by insiders (firm's directors and major shareholders holding more than 3% of the capital) expressed as a percentage of pre-IPO outstanding shares. Directors' options are the directors' holdings of options as a percent of outstanding shares after the IPO. Independent directors' presence is the percent of independent directors on the Board of Directors at the time of the IPO.

2.2 Liquidity measures

Since our hypothesis is that IPO underpricing is not only related to fundamental risk and adverse selection, but also to the expected level of liquidity and its variability, the accurate measurement of liquidity is crucial for our study. To obtain accurate estimates, all our measures of liquidity are based on the first four weeks of after-market trading, using all tick-by-tick data for the mandatory quote period (the interval over which dealers are required to provide firm two-way quotes).

The equilibrium offer price equation in our model (Equation 12 above) indicates that the liquidity measure closest to our model is one that captures the probability of informed trading in the aftermarket. The market microstructure literature provides two potentially suitable measures: first, the PIN measure proposed by Easley et al. (1996), and, secondly, the adverse selection component of the spread. Finally, we can also use the most traditional measure of liquidity, that is, the effective spread.

The PIN measure contains five basic parameters: the probability of arrival of new information (α), the probability that the new information is negative (δ), the arrival rate of informed traders (μ), and the arrival rates of liquidity-based sellers and buyers (ε_s and ε_b). Using this notation, the probability of informed-based orders can be written as

$$\text{PIN} = \frac{\alpha\mu}{\alpha\mu + \varepsilon_s + \varepsilon_b}$$

The maximum likelihood estimation converges for 295 stocks out of the 337 IPOs.

With the spread decomposition, we can extract the adverse selection component of the spread and thereby measure directly the cost due to the presence of informed traders. Among the available spread-decomposition methods, we choose the regression model proposed by Lin, Sanger, and Booth (1995), which appears well suited to measure the impact of informed trading in a dealership market. This method takes changes in transaction prices to reflect order processing costs and the bid-ask bounce, and quote revisions to capture the adverse selection costs.

As a robustness check, we also report estimates based on the most common measure of liquidity: the effective spread, defined as (twice the absolute value of) the percentage difference between the transaction price P and the mid-quote M , that is, $2|P - M|/M$. We use the volume-weighted effective spread, where the effective spread is weighted by the number of shares traded. The effective spread takes into account that trades can occur either inside or outside the quoted spread. It is a good measure of liquidity in dealer markets as it takes into account that dealers give preferential treatment to some customers (preferencing) or match the best quote on

the market (internalization of the order flow). It also avoids the risk of using stale quotes, which is particularly acute on thin markets such as AIM.

We measure liquidity risk by the variability of each of the liquidity variables just mentioned. Our data allow us to measure the variability of liquidity at different frequencies and in various ways. In addition, we can consider measures of dispersion other than the standard deviation, such as the range between the highest and the lowest spread. Experimenting with different sampling frequencies and different measures of dispersion yields highly correlated measures of the variability of effective spreads. We choose to use the range between the highest and the lowest values for both the adverse selection component and the effective spread. The range appears to be both closest to normality among the measures of dispersion considered and the most intuitive from an investor's standpoint. However, this approach cannot be extended to the variability of the PIN because our estimation produces a single PIN measure for each stock for the whole post-IPO period considered. Therefore, in this case we measure liquidity risk by the standard error of the PIN, estimated by two alternative methods: the delta method and a bootstrap method.⁸

Table 3 reports descriptive statistics about underpricing and liquidity and about their evolution in the aftermarket. As shown by Panel A, the

Table 3
Liquidity measures: descriptive statistics

Variable	Mean	Median	Standard deviation	Minimum	Maximum
Panel A: liquidity measures for the entire four weeks of trading					
Liquidity and volatility variables					
PIN	0.286	0.258	0.134	0.042	0.854
Adverse selection component (%)	3.034	2.580	2.117	0.127	8.958
Effective spread (%)	4.112	3.689	2.414	0.291	10.493
Variability of PIN	0.042	0.040	0.018	0.011	0.088
Range of adverse selection component	2.386	1.895	1.625	0.2843	8.614
Range of effective spread	3.554	3.036	2.471	0.329	12.303
Return volatility	0.047	0.028	0.069	0.003	0.42
Daily trading volume (100,000 shares)	20.16	1.31	141.00	0.001	6,100.00
Daily turnover (%)	1.32	0.44	3.10	0.0001	25.87

⁸ The delta method consists of estimating the PINs standard error by using the derivatives of the PIN with respect to each of the parameters (i.e., α , μ , ε_b , ε_s) and the variance-covariance matrix. A detailed description can be found in Green (1993: 297). By the bootstrap method, instead, we generate 10,000 bootstrap samples drawn with replacement for each stock. We use actual data for the first four weeks of trading. We compute the PIN for each bootstrap sample and after obtaining the PIN distribution for each stock we compute the standard error of each distribution. A detailed description is in Efron and Tibshirani (1993: 47). Standard errors obtained by using the bootstrap method are generally smaller than those obtained from the delta method.

Table 3
(continued)

Variable	Mean	Median	Standard deviation "within" firms	Standard deviation "between" firms
Panel B: underpricing and liquidity measures at different horizons				
Underpricing (%)				
1st week	42.21	21.15	7.1086	154.1135
2nd week	38.46	16.41	0.9947	138.4025
3rd week	34.18	12.82	0.1391	125.5471
4th week	29.58	11.36	0.0424	118.2431
PIN				
1st–4th weeks	0.29	0.25	0.0595	0.5462
2nd–5th weeks	0.29	0.25	0.0516	0.5873
3rd–6th weeks	0.27	0.24	0.0563	0.4511
4th–7th weeks	0.26	0.23	0.0463	0.3814
Adverse selection component (%)				
1st week	3.19	3.01	0.8733	3.0219
2nd week	3.15	2.92	0.7571	2.9618
3rd week	3.05	2.81	0.6203	2.8919
4th week	2.98	2.58	0.6525	2.7544
Effective spread (%)				
1st week	4.46	4.15	1.1852	4.0871
2nd week	4.22	3.81	1.0692	4.0041
3rd week	4.01	3.64	1.0473	3.9587
4th week	3.91	3.38	1.0041	3.8154
Turnover (%)				
1st week	4.15	0.91	11.87	19.16
2nd week	2.06	0.56	6.85	8.70
3rd week	1.61	0.35	4.53	3.19
4th week	1.17	0.25	2.75	3.42

The table reports statistics about underpricing and aftermarket liquidity for the 337 IPOs carried out between June 1998 and December 2000 on the London Stock Exchange. Panel A reports statistics for the entire first four weeks of trading while panel B reports underpricing and liquidity measures statistics for each of the first four weeks. The probability of informed trading (PIN) is estimated using the maximum likelihood approach proposed by Easley et al. (1996). The adverse selection component of the spread is obtained using the methodology proposed by Lin, Sanger, and Booth (1995). The effective spread is twice the deviation of the transaction price from the mid-quote price, multiplied by a trade direction dummy and weighted by the number of shares traded. The variability of PIN is the standard error of the PIN estimated for the first four weeks of trading using the delta method. The range of the adverse selection component of the spread is the average of the range between the highest and lowest daily component value. The range of effective spread is the average of the range between the highest and lowest effective spread, calculated for each trading day. Return volatility is the standard deviation of returns using mid-quotes sampled at one-hour intervals. For all these variables, the table shows the pooled time-series and cross-sectional averages across sample firms for the first four weeks of trading on the aftermarket. Underpricing is the percentage change from the offer price to the closing price for each week. Volume transacted is the average daily volume traded in each week. Turnover is the average daily number of shares traded for each week divided by the number of ordinary shares outstanding. In panel B, we define the first week as the first five days of after-market trading. The second, third, and fourth weeks are defined similarly.

average effective spread and the adverse selection component of the spread in the first four weeks of trading are 4.11 and 3.03%, respectively, while the PIN measure is 0.286. The breakdown of these averages across markets (not reported in the table) reveals that, not surprisingly, shares listed on the MM have lower PIN measures than those listed on the AIM: for instance, the average PIN on the MM is 0.207, whereas on the AIM it

is 0.318. The table also shows that the average daily turnover is 1.32% of total outstanding shares. If scaled by the numbers of shares offered at the IPO, the corresponding figure is 4.05%.

Panel B illustrates how underpricing and liquidity evolve over the first four weeks of after-market trading. Average underpricing declines from 42.21% after the first week to 29.58% after the fourth week. Also the PIN and the effective spread decline over the first four weeks of trading. For example, the PIN declines from 0.29 to 0.26 from the first to the fourth week and the effective spread declines from 4.46% in the first week to 3.91% in the fourth week.⁹ There are, however, important differences in the evolution of liquidity in the aftermarket for different types of IPOs. For example, for IPOs effected by bookbuilding and stabilized by the underwriter, the volume-weighted effective spread increases from 0.70% in the first week to 0.81% in the fourth week, and the PIN of these stocks declines from 0.25 to 0.23. A similar pattern is found for the liquidity measures of the IPOs carried out through bookbuilding but not stabilized in the aftermarket: the volume-weighted effective spread for these IPOs increases from 0.81% in the first week to 0.89% in the fourth week while the PIN of these stocks changes only from 0.26 to 0.25 over the same period.

The reduction of the spread may reflect either a decrease in adverse selection (as indicated by the pattern of the PIN and the adverse selection component of spread) as more public information emerges after the IPO or a reduction in fundamental risk or both. Also the different pattern for liquidity observed for IPOs effected through bookbuilding and featuring after-market stabilization is consistent with both explanations. The variability of the spread declines too. The variability “within” firms—that is, the time-series variability of the spread for a given company—shows a more substantial decline than the variability “between” firms. This suggests that the market gradually learns about the liquidity of the firm.

Figures 2 and 3 show that a similar pattern emerges over a longer horizon. The adverse selection component of the effective spread falls from around 3.20% in immediate after-market activity to about 2.40% around the 20th week after the IPO and settles around 1.60% after the 40th week. The PIN and the variability of the adverse selection component of the effective spread decline sharply throughout the first year after the IPO.

The decline in PIN can come from two different sources: 1) the arrival of information (α) or the probability of trading with informed traders (μ) decrease over time; 2) the probability of trading with liquidity traders (ε_s and ε_b) increases over time. Analyzing the various components of the

⁹ The differences between the values of the IPO underpricing, PIN, and effective spread in the first week and in the fourth week are all statistically different from zero at the 5% confidence level.

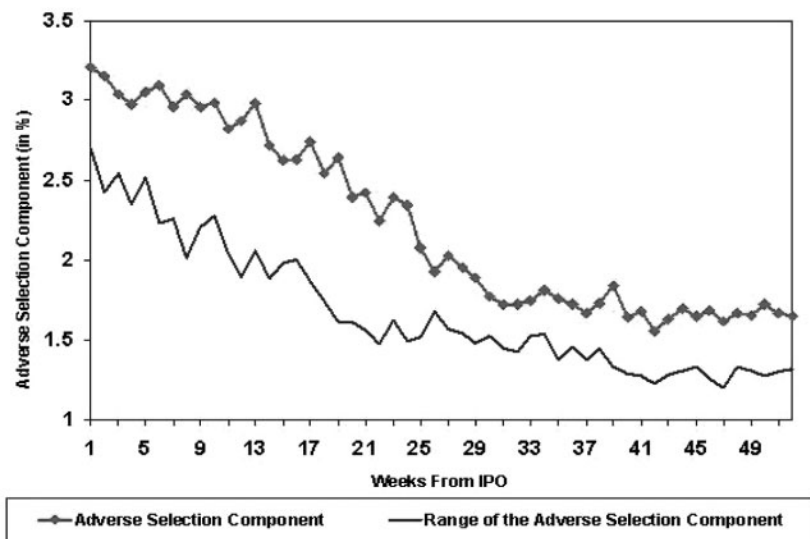


Figure 2

Average adverse selection component of the bid-ask spread and its range of variation in the year after the initial public offering (IPO)

The figure shows the average adverse selection component of the effective bid-ask spread and its range of variation in the first year after the inception of trading for a sample of 337 IPOs carried out in the period June 1998–December 2000.

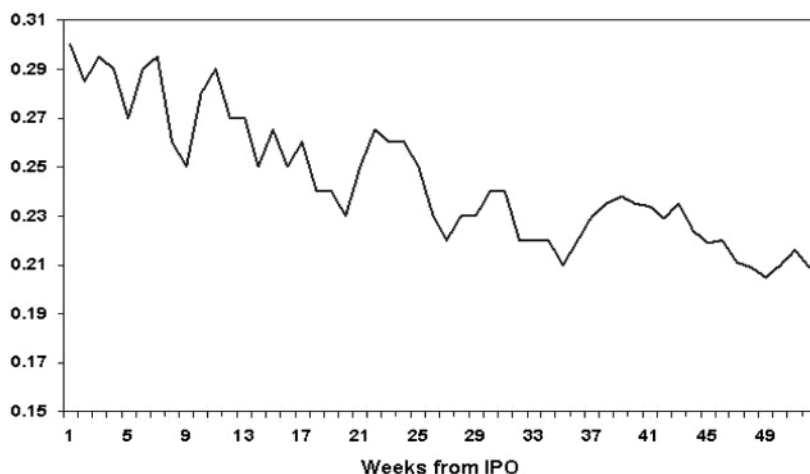


Figure 3

Average probability of informed trading (PIN) measure in the year after the initial public offering (IPO)

The figure shows the average PIN in the first year after the inception of trading for a sample of 295 IPOs carried out in the period June 1998–December 2000. At each date, the PIN is estimated over a moving window of the subsequent four weeks for each stock. The graph shows the cross-sectional average of these measures.

PIN, we find that in the first 40 weeks there are changes in all four parameters. Specifically, α and μ decrease while ε_s and ε_b increase over time. This is consistent with the view that immediate after-market trading is characterized by the substantial presence of informed traders and this results in high adverse selection costs. As expected, as more trading occurs and more information about the firm is released, the market learns more about the firm. Hence, the advantage of informed traders decreases and this may attract more liquidity traders to the market. Of these two effects, the first has the largest marginal impact on the reduction of the PIN: we find that the impact generated by the reduction of α and μ is greater than the increase in ε_s and ε_b .¹⁰

This pattern suggests that both liquidity and its variability are much more of a problem in the immediate after-market trading than in a more mature market. Therefore, a rational IPO investor who reckons that she might have to liquidate in the immediate aftermarket or plans to do so should be much more concerned about liquidity than a buy-and-hold investor. This calls for focusing the analysis of the relationship between IPO returns and liquidity on the first few weeks of after-market trading. As we move away from the IPO date, investors face an increasingly liquid market and a more predictable spread so that trading costs should become less of a concern for them. Finally, confounding events may increasingly cloud the IPO price–liquidity relationship.

Our data indicate that liquidating shares in the aftermarket does not appear to be a rare event. Despite the abnormally high trading costs immediately after the IPO, it is precisely at that time that trading activity peaks, possibly reflecting the frantic activity of “flippers.” As shown by Panel B of Table 3, trading activity is heaviest in the first week and then declines steadily. While the table reports only turnover, all the other relevant measures—for example, number of trades and waiting time between trades—agree on this point. That the abnormally large after-market trading costs are incurred so frequently suggests that IPO investors are unlikely to neglect them.

3. Methodology and Results

Our main objective is to investigate how IPO underpricing is affected by expected liquidity and liquidity risk as perceived by investors at the time

¹⁰ Keeping the initial values of α and μ fixed at the initial levels obtained for the first four weeks and letting only the values of ε_s and ε_b change would decrease PIN from the initial value of 0.29 to 0.27 in the period that spans from the 10th to the 14th weeks and later to 0.26 in the period spanning the 20th to the 24th weeks. Instead, keeping the initial values of ε_s and ε_b fixed at those obtained over the first four weeks and letting only the values of α and μ change would decrease PIN from the initial value of 0.29 to 0.26 in the period that spans from the 10th to the 14th weeks and 0.24 in the period spanning the 20th to the 24th weeks.

of the IPO. In this exercise, we control for other factors, whose role has already been tested in the literature.

In our baseline approach, we measure expected liquidity and liquidity risk by the sample moments of the relevant variables, such as the mean and standard error of the PIN and the mean and range of variation of the spread's adverse selection component. Simple correlations already indicate that IPO underpricing is larger for IPOs with lower and more variable after-market liquidity, as illustrated by Figures 4 and 5. The correlation between IPO underpricing and the average PIN measured over the first four weeks of after-market trading is 0.25, statistically significant at the 1% confidence level. Likewise, the correlation between IPO underpricing and the range of the PIN is 0.35, statistically significant at the 1% confidence level. Similar figures are obtained if after-market illiquidity is measured by the effective spread or with its adverse selection component. However, since the sample moments of these illiquidity measures may measure market expectations with error, below we rely on instrumental variables (IV) estimation.

Moreover, the sample moments of liquidity measured over the first four weeks of the aftermarket are unconditional estimates of the expected value and the variance of liquidity. The IPO offer price should instead reflect conditional expectations, that is, the expected value, and the variance of liquidity conditional on the variables known to investors at the time of the IPO. To take this further point into account, we also

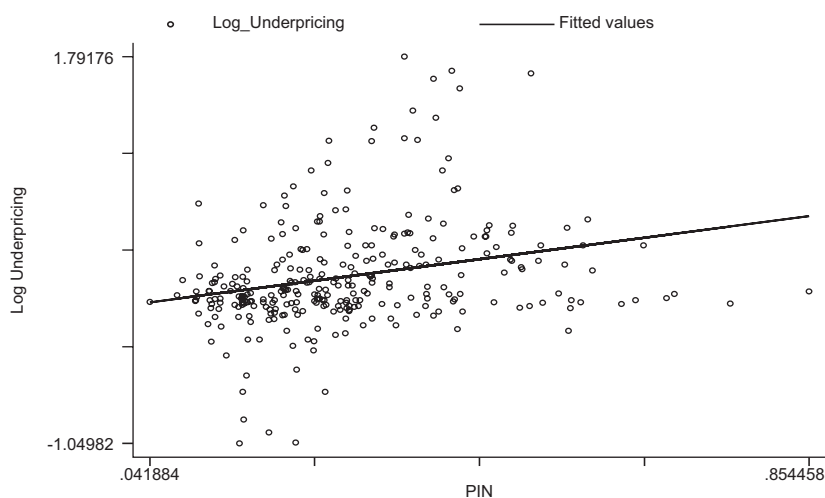


Figure 4

Log underpricing and the probability of informed trading (PIN)

The figure plots data for log underpricing and the PIN. Log underpricing is the natural log of the ratio between the closing price on the first day of trading and the initial public offering (IPO) price. The PIN is the average PIN in the first four weeks of after-market trading. The straight line in the figure shows the predicted values of an OLS regression of log underpricing on a constant and the PIN.

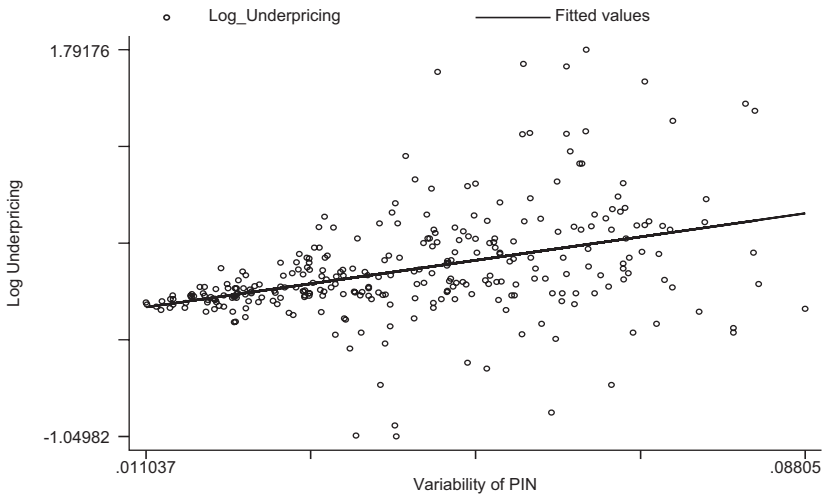


Figure 5

Log underpricing and the variability of the probability of informed trading (PIN)

The figure plots data for log underpricing and the variability of the PIN. Log underpricing is the natural log of the ratio between the closing price on the first day of trading and the initial public offering (IPO) price. The variability of the PIN is the standard error of the PIN over the first four weeks of trading (using the delta method). The straight line in the figure shows the predicted values of an OLS regression of log underpricing on a constant and the variability of the PIN.

implement a second methodology, where our measure of expected liquidity and liquidity risk conditions only on firm characteristics known at the IPO stage.

Even this measure of expected liquidity may be questioned if the regressors used to forecast liquidity are proxying for other determinants of the IPO discount. To check the robustness of our results to this problem, we use a third methodology, based on a matched-firm approach: we assume that to forecast an IPO's future liquidity and its variability, investors impute to it the values observed for a previous IPO of comparable size and belonging to the same sector.

Throughout the estimation, in keeping with our model we measure underpricing as the natural log of the ratio of the after-market price to the offer price ($\log(P_1/P_0)$). This measure differs slightly from that used in the literature, which is the percent return from the offer price to the after-market price $[(P_1 - P_0)/P_0]$. We rely on the former measure of underpricing for two reasons. First, according to the theoretical model presented in Section 1, if utility is logarithmic the ratio between the after-market price and the offer price holds a convex relationship with the explanatory variables that we employ. In this case, as shown by Equation (15''), a logarithmic transformation of the dependent variable is appropriate. Secondly, from a statistical point of view, the $\log(P_1/P_0)$ is much

closer to a normally-distributed variable than the measure $(P_1 - P_0)/P_0$ so far used in the literature. In particular, the skewness and kurtosis of our underpricing measure for the first day are 1.16 and 6.90, respectively, compared with 3.84 and 22.08 for the traditional measure. Likewise, the skewness and kurtosis of our underpricing measure for the first four weeks are 1.10 and 6.68, respectively, and 2.97 and 14.46 for the traditional measure. However, we also test our empirical model by using the traditional measure of underpricing and find that the estimates are qualitatively unchanged.

We measure underpricing over various different horizons. In our baseline estimates, the horizon is the first four weeks of trading: we measure the after-market price P_1 as the closing price of the 20th trading day to ensure consistency between the time period over which we measure liquidity and the time period used to calculate underpricing. But, as a robustness check, we repeat the estimation by using a measure closer to the existing IPO literature, that is, by defining P_1 as the closing price of the *first* trading day. Finally, we repeat the estimation with underpricing measured over other horizons: the first week, second week, and third week of after-market trading.

3.1 Model specification

Consistently with the model presented in Section 1, we wish to nest our liquidity-based explanation of IPO underpricing with the two main explanations advanced in the literature: fundamental risk and asymmetric information. Therefore, the specifications used in previous work to test these hypotheses are our natural starting point. Table 4 presents the list of explanatory variables that we employ in our specification.

Liquidity. Our model predicts both after-market liquidity and liquidity risk to have positive coefficients. The more liquid the secondary market is expected to be, the lower the liquidity premium that IPO underpricing must incorporate. Similarly, the harder it is to predict liquidity, the higher the return required by investors at the IPO stage. As already mentioned, we rely on various measures of liquidity, of which the one that comes closest to our model is the estimated probability of an informed trade as captured by the PIN proposed by Easley et al. (1996). We also use a related measure: the adverse selection component of the spread proposed by Lin, Sanger, and Booth (1995). Finally, as a robustness check, we also measure liquidity simply by the effective bid-ask spread.

Asymmetric information. The amount of shares sold by the insiders is a key variable to gauge the presence of asymmetric information in the IPO process. If the initial owners know that their company is of low quality, at the IPO stage they will sell a large stake, as in the adverse selection model

Table 4
Model specification

Source of underpricing	Explanatory variables	Predicted sign of coefficient
Liquidity	Probability of informed trading	Positive
	Adverse selection component of spread	Positive
	Effective spread	Positive
Liquidity risk	Variability of liquidity variables	Positive
Adverse selection	Sales by insiders	Ambiguous
	Directors' holdings of options	Ambiguous
	Venture capitalists' presence	Negative
	Bookbuilding mechanism	Positive
	Underwriter reputation	Negative
	Independent directors' presence	Negative
	Number of previous IPOs	Negative
	Total proceeds of previous IPOs	Negative
	Size of firm (total assets)	Negative
	Firm's age	Negative
Fundamental risk	Return volatility	Positive
	High-risk sector (information technology sector)	Positive
	Underwriter stabilization	Positive
	IPO size (proceeds from offering)	Positive

IPOs, initial public offerings.

by Leland and Pyle (1977). The same prediction holds in a moral hazard model such as Jensen and Meckling (1976): the higher the stake sold by controlling shareholders, the higher is their incentive to extract private benefits at the expense of minority shareholders. In both cases, the insiders' decision to sell a large stake is bad news for the market and therefore should induce higher underpricing.

In an environment where managers are partly compensated through options, especially in young and R&D-intensive firms, the attribution of options to management can play the same role as a larger insiders' stake, both as quality signal and as incentive device. Up to now, the literature has not used this variable to explain underpricing, perhaps due to lack of data. But since this information is available in IPO prospectuses, we use it as an additional test of the Leland–Pyle and Jensen–Meckling predictions.

However, the logic of these models is not unchallenged: Habib and Ljungqvist (2001) argue that initial owners who sell a large stake will want as little underpricing as possible and can do so by spending more resources on “promotion activities.” Their prediction is that underpricing is decreasing in the amount of shares that insiders sell at the IPO. As a result, the relationship between insiders' sales (or directors' amount of options) and underpricing is in principle ambiguous.

With asymmetric information, the presence of a venture capitalist can be a quality signal, leading to lower underpricing (Barry et al. 1990; Megginson and Weiss, 1991). Therefore, a dummy variable for the

presence of a venture capitalist should carry a negative coefficient. Since venture capitalists typically enter the shareholder base long before the IPO, this variable is predetermined relative to the offer price. By the same token, the reputation of the underwriter can reduce underpricing as found by Carter and Manaster (1990).

The amount of private information that remains undisclosed after the IPO also depends on characteristics of the IPO design. Busaba and Chang (2002) show that, compared with a fixed-price offering, the bookbuilding process elicits more information from informed traders at the IPO stage and therefore reduce adverse selection problems in the after-market trading. However, by the same token bookbuilding may require larger informational rents to be paid at the IPO stage as found by Ljungqvist, Jenkinson, and Wilhelm (2003). This suggests that underpricing should be larger for IPOs carried out through bookbuilding than through a fixed-price method.

Finally, the offer price of each company can be affected by the earlier IPO activity in the market or in the same sector because of information spillovers. Previous IPOs can provide guidance about the investors' appetite for the company's shares and thus about the price they are willing to pay. Benveniste et al. (2003) provide evidence that underpricing is lower when many IPO issues were floated in the recent past. Consistent with such evidence, we expect a negative coefficient on the number and the proceeds of the IPOs carried out in the previous and current quarters.

Fundamental risk. We control for fundamental risk by predetermined variables such as size (measured by the logarithm of total assets), age (measured by logarithm of the number of years since incorporation),¹¹ and sector of the company, and more directly by the volatility of after-market returns. We measure the latter by calculating the standard deviation of returns using mid-quotes (to avoid potential problems caused by the bid-ask bounce) sampled at one-hour intervals over the first four trading weeks. We expect underpricing to be higher for shares with greater after-market return volatility. But the latter may not fully measure the risk of IPO shares: then age, size, and sector could still play a role. If so, IPO underpricing should be lower for issues of older and larger companies, which generally feature less risk. The opposite should be true of IPOs undertaken by companies in the information technology (IT) sector as shown by Loughran and Ritter (2004) on US data. This is important for our sample, which includes the Internet bubble. Hence, we would expect the coefficients of return volatility and an IT dummy to be positive and those of size and age to be negative.

¹¹ Firms' age and size can proxy for both risk and adverse selection. For example, age should be inversely related to risk, insofar as companies grow into more diversified businesses over time, as well as to adverse selection because mature companies have a longer track record.

The impact of the total IPO proceeds may also capture the effect of risk. Investors may require an extra return to “digest” very large IPOs because to purchase the implied stakes they may have to accept at least some temporary imbalance in their portfolios. However, from the econometric point of view this variable cannot be considered as exogenous, in the same sense in which the quantity sold by a monopolist cannot be regarded as exogenous with respect to the price chosen. This applies also to other characteristics of IPOs, such as insiders’ sales, which are chosen by the issuers jointly with the level of underpricing at the time of the IPO. Despite such endogeneity problems, these variables have been extensively used in past empirical work. When we include them as regressors, we attempt to control for their possible endogeneity. Finally, to control for any clustering that may occur, we also include year dummy variables in every specification.

Since our specification includes several variables to control for the informational asymmetries at the IPO stage, our measures of liquidity should capture only the “residual asymmetric information” that persists in secondary market trading. Admittedly, some of our explanatory variables may be correlated also with this “residual asymmetric information.” For instance, for older and larger firms information asymmetries may be less pronounced both at the IPO stage *and* in the aftermarket. So the inclusion of age and size in the regressions may reduce the explanatory power of after-market liquidity, insofar as it reflects “residual asymmetric information.” So, if anything, the inclusion of such regressors should bias the coefficient of the liquidity variables toward zero.

3.2 Instrumental variable estimates

Our baseline approach is to measure the expected value and the variance of after-market liquidity by the two corresponding sample moments, computed over the first weeks of trading. This method rests on the assumption that at the time of the IPO investors correctly anticipate the true moments of these variables, of which the corresponding sample moments are unbiased estimates. But the ex-post average and variance of liquidity may measure with error the estimates held by investors, making the estimated coefficients inconsistent and biasing them toward zero. These problems may be compounded by the potential endogeneity of after-market liquidity with respect to IPO underpricing. Higher underpricing may induce greater market participation by retail investors [as argued by Brennan and Franks (1997) and Booth and Chua (1996)]. If this increases after-market liquidity, our measures of liquidity may be correlated with the error of the underpricing equation.

To correct for these problems, we rely on IV estimation. The instrument for the liquidity variables are (i) the average daily volume of firms that are already public in the same industrial sector in the four weeks before an IPO, (ii) the industry’s return volatility in the four weeks before

an IPO, (iii) the fraction of the share capital held by the major shareholders after the IPO, (iv) the log of the amount of new shares issued in the IPO, (v) the IPO mechanism (“placing” versus “offer”), (vi) the market on which the IPO is carried out, and (vii) the industrial sector. Based on the empirical literature and on “a priori” reasoning, these variables are likely to be correlated with after-market liquidity.¹²

Endogeneity problems may also affect the amount of shares sold by insiders and the size of the IPO, since these are chosen by the company jointly with the offer price. Therefore, we instrument also these variables with (i) the company’s sales (in logs) in the year before the IPO and (ii) the leverage ratio just before the IPO.¹³

3.3 Forecasting liquidity through firm-level regressions

Our second approach relies on conditional measures of expected liquidity and of its variability, based on the liquidity of previously listed companies and conditioning on the following variables: (i) industrial sector, (ii) size (by total assets), (iii) the leverage ratio, (iv) the concentration of the share capital held by the major shareholders after the IPO, (v) the IPO mechanism, and (vi) the market on which the IPO is carried out. For every IPO in our sample, we estimate a regression that uses all the observations for the firms that went public up to that date. The fitted values from each regression are then used as measures of investors’ expectation about the future liquidity and liquidity risk of the IPO being considered. This method runs into the problem of lacking observations for the first IPOs in our sample, that is, those occurring in 1998. Since no price and quote data are provided by the LSE for the period between July 1996 and May 1998, we resort to the data for IPOs carried out in the first half of 1996 to forecast the liquidity of the IPOs of 1998.

3.4 Forecasting liquidity through a matched-firm approach

Our third method is to impute expected liquidity and the associated risk from those of previous IPOs matched by industry and size. This method differs

¹² The empirical literature shows that past trading volume and return volatility are major factors influencing liquidity. The concentration of the share capital, that is, the amount of the share capital closely held by the major shareholders, determines how much of the firm’s share capital is publicly traded and thus directly influences the firm’s liquidity. (We leave the *sales* by the initial main shareholders to capture the signal sent to the market regarding the firm’s quality.) Also the IPO mechanism can be regarded as a good predictor of after-market liquidity, because it should contribute to determine the amount of private information that is revealed at the IPO stage and thereby the residual informational asymmetries left in after-market trading. The choice of IPO mechanism is a dummy variable indicating whether the IPO occurred through (i) a “placing” (similar to the firm commitment in the United States), which is entirely addressed to institutional investors, or (ii) a “public offer”, addressed both to institutional investors and retail investors. Finally, since typically market liquidity is higher on the Main Market (MM) than on the Alternative Investment Market (AIM), the list of instruments includes a dummy variable indicating whether shares were floated on the MM or the AIM.

¹³ The R^2 of the first-stage regressions for the amount of shares sold by insiders and for the size of the IPO are 0.174 and 0.204, respectively.

from the previous one, in that it uses actual liquidity of previous IPOs rather than a forecast obtained from a regression methodology. Every IPO in our sample is matched with a previous IPO in the same industry and closest in size, provided that the size difference does not exceed 10%. When the difference is larger than 10% we match the current IPO with the two previous IPOs (in the same sector) closest in size to the current IPO, and in the analysis we use their volume-weighted average liquidity and risk.

This method, like the one before it, runs into the problem of lacking observations for the IPOs occurring in 1998. As in the previous method, we use data on IPOs carried out in the first half of 1996 to forecast the liquidity of the 1998 IPOs.

3.5 Results

In Table 5, we report the regression estimates obtained from the different methodologies illustrated so far, for each of the liquidity measures (PIN

Table 5
Regression results

Liquidity measure	PIN	Adverse selection component	Effective spread
Panel A: instrumental variable regressions			
Intercept	0.3252 (0.61)	0.6442 (1.34)	0.4871 (1.03)
Liquidity	0.9444** (2.02)	0.0582* (1.93)	0.0563* (1.90)
Variability of liquidity	8.1572** (1.96)	0.0638* (1.80)	0.0459* (1.91)
Sales by insiders	-0.0005 (-0.12)	0.0005 (0.15)	0.0005 (0.14)
Directors' options holdings	-0.0015 (-0.26)	-0.0040 (-0.77)	-0.0034 (-0.62)
Venture capitalist's presence	-0.1042** (-2.40)	-0.0938** (-2.46)	-0.1025*** (-2.62)
Firm age	-0.0441* (-1.68)	-0.0449* (-1.91)	-0.0400* (-1.71)
Total assets	0.0019 (0.20)	-0.0004 (-0.04)	-0.0004 (-0.05)
Governance	0.0015 (0.81)	0.0011 (0.64)	0.0014 (0.81)
Return volatility	0.9928** (1.98)	1.1740*** (2.90)	1.0768*** (2.66)
IT sector	0.0132 (0.26)	0.0066 (0.14)	0.0248 (0.52)
IPOs in the same quarter	-0.0516 (-0.58)	-0.0218 (-0.27)	-0.0203 (-0.25)
IPOs in the previous quarter	-0.1608* (-1.64)	-0.1998** (-2.19)	-0.1856** (-2.15)
Underwriter stabilization	0.1626* (2.69)	0.1351* (2.22)	0.1469** (-2.35)
Underwriter reputation	-0.0190* (-1.66)	-0.0196** (-2.03)	-0.0204** (-2.02)
Bookbuilding	0.0378 (0.55)	0.0703 (1.31)	0.0688 (1.25)
Size of the IPO	0.0235 (0.77)	0.0251 (0.87)	0.0276 (0.88)
R ²	0.27	0.26	0.24
Number of observations	295	337	337
Panel B: regressions with liquidity measures from regression-based forecasts			
Intercept	1.1845*** (3.33)	0.7398*** (2.97)	0.8163*** (3.15)
Liquidity	0.5041* (1.91)	0.0254* (2.70)	0.0195** (2.03)
Variability of liquidity	1.788* (1.88)	0.0446* (1.80)	0.0235* (1.91)
Directors' options holdings	-0.0065 (-1.21)	-0.0080 (-1.58)	-0.0067 (-1.28)
Venture capitalist's presence	-0.0832** (-2.15)	-0.0951** (-2.54)	-0.1008*** (-2.63)
Firm age	-0.0645*** (-3.12)	-0.0566*** (-2.78)	-0.0657*** (-3.22)
Total assets	-0.0060 (-0.79)	-0.0026 (-0.37)	-0.0012 (-0.16)
Governance	0.0004 (0.25)	0.0008 (0.53)	0.0010 (0.65)
Return volatility	1.4632*** (3.76)	1.3198*** (3.40)	1.4405*** (3.70)
IT sector	0.0092 (0.20)	0.0165 (0.36)	0.0110 (0.23)
IPOs in the same quarter	-0.0879 (-1.06)	-0.0632 (-0.82)	-0.0859 (-1.09)
IPOs in the previous quarter	-0.2127*** (-2.70)	-0.2253*** (-2.81)	-0.2200*** (-2.67)
Underwriter stabilization	0.0458 (1.05)	0.0852** (1.95)	0.0860** (2.00)

Table 5
(continued)

Liquidity measure	PIN	Adverse selection component	Effective spread
Underwriter reputation	-0.0138** (-1.98)	-0.0126* (-1.81)	-0.0151** (-2.15)
Bookbuilding	0.1124* (1.83)	0.1037* (1.81)	0.1095* (1.84)
R ²	0.28	0.32	0.27
Number of observations	337	337	337
Panel C: regressions with liquidity measures from matched-firm forecasts			
Intercept	1.1878*** (3.14)	1.1068*** (2.90)	1.1672*** (3.04)
Liquidity	0.5376** (2.11)	0.0279** (2.10)	0.0248* (1.91)
Variability of liquidity	4.7521* (1.94)	0.0682* (1.83)	0.0277** (2.21)
Directors' options holdings	-0.0051 (-0.98)	-0.0076 (-1.49)	-0.0069 (-1.32)
Venture capitalist's presence	-0.0977** (-2.53)	-0.0947** (-2.51)	-0.1054*** (-2.77)
Firm age	-0.0583*** (-2.79)	-0.0538** (-2.51)	-0.0593*** (-2.86)
Total assets	-0.0028 (-0.38)	-0.0025 (-0.36)	-0.0025 (-0.33)
Governance	0.0009 (0.54)	0.0009 (0.58)	0.0010 (0.62)
Return volatility	1.4136*** (3.81)	1.3438*** (3.51)	1.4105 (3.78)
IT sector	0.0252 (0.55)	0.0239 (0.52)	0.0247 (0.53)
IPOs in the same quarter	-0.0652 (-0.84)	-0.0503 (-0.66)	-0.0578 (-0.74)
IPOs in the previous quarter	-0.2738*** (-3.43)	-0.2526*** (-3.30)	-0.2473*** (-3.13)
Underwriter stabilization	0.0922** (2.17)	0.0930** (2.09)	0.0900** (1.98)
Underwriter reputation	-0.0154** (-2.09)	-0.0127* (-1.84)	-0.0152** (-2.12)
Bookbuilding	0.1025* (1.78)	0.0973* (1.76)	0.1009* (1.79)
R ²	0.27	0.30	0.28
Number of observations	337	337	337

The dependent variable is the IPO underpricing, defined as the natural log of the ratio between the closing price of the 20th day of trading and the IPO offer price. Panel A reports the coefficient estimates from an instrumental variables (IV) estimation where we instrument for the level and variability of the liquidity measures (PIN, adverse selection component of the spread, or effective spread) for sales by insiders and for IPO proceeds. Panel B reports the coefficient estimates using regression forecasts of each liquidity measure based on pre-IPO information. Panel C reports the coefficient estimates using forecasts of each liquidity measure based on size- and sector-matched firms. The PIN is estimated using the maximum likelihood approach proposed by Easley et al. (1996). The variability of the PIN is the standard error of the PIN estimated for the first four weeks of trading using the delta method. The adverse selection component of the spread is obtained using the methodology proposed by Lin et al. (1995) on effective spread data. The variability of the adverse selection component of the spread is the range between the highest and lowest daily component value for the first four weeks of trading. The effective spread is twice the deviation of the transaction price from the mid-quote price, multiplied by a trade direction dummy and weighted by the number of shares traded, over the first four weeks of trading. The variability of the effective spread is the average range between the highest and lowest effective spreads, calculated for each trading day over the first four weeks of trading. Sales by insiders are the shares sold at the IPO stage by the main shareholders as percent of the total shares outstanding at the time of the IPO. Directors' options are the directors' holdings of options as a percent of outstanding shares after the IPO. Venture capitalist is a dummy variable that equals 1 if the company had a venture capitalist as one of its main shareholders at the time of the IPO and 0 otherwise. Total assets is the log of the sum of fixed assets and current assets in the year preceding the IPO, in thousand pounds. Firm age is the log of the number of years from the firm's original incorporation to the time of the IPO. Governance is the ratio of independent directors to total number of directors in the firm's Board of Directors. Return volatility is the standard deviation of returns using mid-quotes sampled at one-hour intervals over the first four trading weeks. IT sector is a dummy variable that takes the value of 1 if the company operates in the information technology sector and 0 otherwise. Number of IPOs in the same (previous) quarter is the log of the number of IPOs carried out on the London Stock Exchange (LSE) in the same (previous) quarter relative to every IPO in the sample. Underwriter stabilization is a dummy variable that equals 1 when a stabilization agreement is mentioned in the IPO prospectus and 0 otherwise. Bookbuilding is a dummy variable that equals to 1 if the bookbuilding mechanism is used and to 0 otherwise. Size of the IPO is the log of the total IPO proceeds. Underwriter reputation is the market share of each underwriter of the total IPO proceeds in the twelve months before the IPO. Year dummies (not reported) are included as explanatory variables. Asterisks (*, ** and ***) indicate statistical significance (at the 10%, 5% and 1% level respectively).

in the first column, the adverse selection component in the second column, and the effective bid-ask spread in the third column). The *t*-statistics are based on robust standard errors, computed using the Huber–White estimator.

The overall explanatory power of the regression shown in Panels A–C is satisfactory compared with those reported in previous studies of IPO underpricing since it accounts for at least 25% of the variance in the dependent variable. The coefficients of all the explanatory variables carry the signs predicted in Table 4, except for the corporate governance variable (i.e., the fraction of independent directors), whose coefficient is positive though not statistically significant.

Impact of liquidity. All measures of liquidity and its variability have positive coefficients. These coefficients are not only statistically significant (some at the 5% and others at the 10% confidence level), but also economically significant.¹⁴ In particular, the IV estimates imply that a one standard deviation (SD) increase in the PIN (from its average level of 0.286 to 0.42) is associated with an increase of 16 percentage points in underpricing,¹⁵ though the impact is lower in the firm-level and matched-firm regressions. Likewise, increasing the standard error of the PIN by one SD (from its average value of 0.042 to 0.06) increases underpricing by almost 19 percentage points.¹⁶ A one SD increase in the adverse selection component of the spread and in its range of deviation have comparable effects on underpricing: 15.5 and 13 percentage points, respectively. Similar estimates are obtained also for a one SD increase in the effective bid-ask spread itself and its variability: 17 and 14 percentage points, respectively.

The impact of liquidity and its variability is significantly smaller when they are estimated conditionally only on information available at the time of the IPO. For example, Panel B shows that liquidity is forecast by regression analysis, a one SD increase in the PIN is associated with an increase of 8.3 percentage points in underpricing.¹⁷ Likewise, increasing the standard error of the PIN by one SD increases underpricing by almost 4 percentage points. Similarly, a one SD increase in the adverse selection component of the spread increases underpricing by 7 percentage points and

¹⁴ The correlation between underpricing and the PIN measure (adverse selection component) is 26% (28%), whereas the correlation between underpricing and the standard error of the PIN (range of the adverse selection component) is 39% (34%).

¹⁵ This estimate is obtained by taking the difference between the antilog of the dependent variable's predicted value conditional on a one SD increase in the PIN and the antilog of the dependent variable's sample mean.

¹⁶ A one SD increase in the liquidity risk when the bootstrap methodology is used (instead of the delta method) is 14%.

¹⁷ This estimate is obtained by taking the difference between the antilog of the dependent variable's predicted value conditional on a one SD increase in the PIN and the antilog of the dependent variable's sample mean.

the same increase in its range of variation increases underpricing by 8 percentage points.

Considering that fundamental risk and adverse selection are already controlled for by the inclusion of other variables, it is remarkable that the level and the variability of the liquidity measures have such a large and precisely estimated impact on IPO underpricing.

Impact of company and IPO characteristics. In Table 5, the coefficients of all the variables that according to the literature may capture the role of informational asymmetries at the IPO stage have the predicted sign. According to the estimates, underpricing is significantly lower when directors have large holdings of options in the post-IPO firm, when a venture capitalist has a stake in the company at the time of the IPO and when the shares are sold by an underwriter with a solid reputation (as measured by market share in the previous year's IPOs).¹⁸ The bookbuilding method appears to be associated with higher underpricing, as expected, although in the baseline specification shown in the first column its estimated coefficient is not significantly different from zero. Finally, in line with the information spillover hypothesis, underpricing is significantly lower if more IPOs are carried out in the previous quarter, though not in the current one.¹⁹

As predicted by risk-aversion models, older companies face less underpricing when they go public while the opposite holds for companies with more volatile after-market returns, other things equal. The coefficient of the total assets is not always negative, as predicted, but it lacks statistical significance. This reflects collinearity with the age variable: the log of total assets has a strong correlation (0.58) with the firm's age, and its coefficient becomes significant at the 1% confidence level if age is dropped.

The IT Sector dummy, which identifies IPOs in the IT industry, has a positive but imprecisely estimated coefficient. Also the fraction of independent directors, that many view as a mechanism to improve a firm's corporate governance, does not affect significantly the level of underpricing, possibly because of its endogeneity.

The underwriter's stabilization in the aftermarket is a further control variable. The literature shows that underwriters do stabilize the IPO in

¹⁸ Since the quality of the underwriter is to a certain extent under the control of the initial owners of the company, according to Habib and Ljungqvist (2001) the estimate of its coefficient may be biased by endogeneity problems, which may account for the positive relation between underpricing and underwriter reputation documented by Beatty and Welch (1996). However, in our data the relation between the two variables is negative as in the initial study by Carter and Manaster (1990).

¹⁹ If IPO activity is measured by the proceeds rather than by the number of recent IPOs, the spillover is contemporaneous, not lagged as in Table 5. In such a specification (data not shown), the coefficient of the IPO proceeds in the same quarter is negative (-0.0535) and statistically significant at the 1% level, whereas the coefficient of current IPO proceeds is not statistically significant.

the very first days of after-market trading. Stabilization could be a potential problem for our estimates if we do not control for it since it may increase both the degree of underpricing and the liquidity in the market. The stabilization dummy variable indicates if a stabilization agreement is mentioned in the IPO prospectus, which happens in several medium-sized and large IPOs (mainly undertaken on the MM). As expected, the coefficient of this variable is positive, in agreement with the evidence reported by Ruud (1993).

Finally, in the IV estimation we find that the IPO proceeds carry a positive coefficient, consistently with signaling and agency models, but lacks statistical significance. Likewise, the coefficient of sales by insiders lacks statistical significance.

3.6 Robustness checks

A potentially controversial issue is over which period we should measure underpricing, liquidity, and its risk. This amounts to asking what is the typical trading horizon relevant for IPO investors. Different time horizons will be relevant for different “types” of liquidity-motivated traders.

The statistics reported in Table 3 show that trading activity is abnormally high in the first few days in the aftermarket. This suggests that “flippers” are likely to be a considerable fraction of the initial IPO investors. However, since underpriced IPOs attract substantial interest from investors who are often severely rationed at the time of the offer, the large volumes transacted in the very first days may also reflect pent-up demand for these securities by long-term investors. The decision on the appropriate time horizon for our analysis must also trade-off the benefit from a more accurate measurement of liquidity associated with a longer interval and the danger of including confounding events (such as news releases) that can affect liquidity and its variability.

We test the robustness of our results to changes in the holding period in two directions. First, we shorten the horizon over which we measure underpricing, computing it relative to the closing price of the first trading day as customary in the IPO literature while relying on the same liquidity variables used as explanatory variables in Table 5. Comparing the coefficient estimates obtained by this method with those shown in Table 5, we find that the impact from liquidity and its risk on underpricing is robust to the choice of the holding period.

We also check the robustness of our results to the type of market used for the IPO. In principle, the impact of liquidity and liquidity risk on IPO underpricing may differ depending on the type of market used by the issuer to carry out the IPO. Liquidity and its risk are likely to play a more important role in the IPO underpricing for firm listing on the AIM since small firms are notoriously less liquid than larger firms. We address this concern by re-estimating the model separately for MM and AIM IPOs.

We find that, though liquidity is priced for IPOs on both MM and AIM, the estimated impacts of liquidity and liquidity risk on underpricing are generally larger for companies listed on the AIM.

4. Conclusions

Does after-market liquidity matter for IPO underpricing? In this article we show that it does. Investors participating in IPOs want to be compensated not only for the firm's fundamental risk and adverse selection costs in the IPO process, but also for the expected liquidity of the shares they are buying and for the risk of an illiquid secondary market.

At the theoretical level, we make this point by a model where IPO underpricing is affected not only by adverse selection at the IPO stage and by fundamental risk, but also by the asymmetric information that they expect to persist in after-market trading and by the implied trading costs. Our setting can accommodate also the potential for different liquidity regimes and therefore formalizes the notion of "liquidity risk" as distinct from fundamental risk as well as from the expected level of liquidity. The model nests nicely traditional explanations and our liquidity-based view of IPO underpricing.

We test for the presence of liquidity effects on IPO underpricing after controlling for the variables suggested by other theories of IPOs. In line with the model, in measuring liquidity we focus particularly on the portion of after-market trading costs that can be attributed to asymmetric information. Using a sample of companies that went public on the LSE between June 1998 and December 2000, we find that expected after-market liquidity and liquidity risk are important determinants of IPO underpricing, even though we control for all the other factors that have traditionally been used to explain underpricing. The results are robust to the use of alternative measures of expected liquidity and of liquidity risk. They are also robust to corrections for measurement error and endogeneity of the liquidity variables to different holding periods and to splits across market segments. These results highlight an important and neglected link between market microstructure and corporate finance: secondary market liquidity affects the cost of equity capital for companies that choose to go public.

Appendix

Derivation of equation (15)

Under risk aversion, Equation (1) must be restated in terms of expected utility: investor j bids for shares at the IPO only if

$$zE\left[U(\tilde{P}_1|\Omega_0^j)\right] + (1-z)E\left[U(\tilde{P}_2|\Omega_0^j)\right] \geq U(P_0). \quad (\text{A1})$$

Therefore, the informed investors' bids will impound their private information $\tilde{u}_1$ only if

$$zE[U(\tilde{P}_1^B|\tilde{u}_1 = \eta)] + (1-z)E[U(\tilde{P}_2|\tilde{u}_1 = \eta)] \geq U(P_0) > zE[U(\tilde{P}_1^B|\tilde{u}_1 = -\eta)] + (1-z)E[U(\tilde{P}_2|\tilde{u}_1 = -\eta)], \quad (A2)$$

which, using Equation (2) and recalling that $\tilde{P}_2 = V + \tilde{u}_1 + \tilde{u}_2$, can be rewritten as

$$zU\left(V + \eta - \frac{q}{q+z}\varepsilon\right) + \frac{1-z}{2}[U(V + \eta + \varepsilon) + U(V + \eta - \varepsilon)] \geq U(P_0) > zU\left(V - \eta - \frac{q}{q+z}\varepsilon\right) + \frac{1-z}{2}[U(V - \eta + \varepsilon) + U(V - \eta - \varepsilon)]. \quad (A3)$$

If condition (A3) holds, the informed traders' optimal strategy is to bid only if $\tilde{u}_1 = \eta$. We shall see that this condition is met in equilibrium, if uninformed investors participate.

From (A1), uninformed investors instead bid for shares if

$$z[\pi_u U(\tilde{P}_1^B|\tilde{u}_1 = \eta) + (1-\pi_u)U(\tilde{P}_1^B|\tilde{u}_1 = -\eta)] + (1-z)\pi_u \left[\frac{1}{2}U(\tilde{P}_2|\tilde{u}_1 = \eta, \tilde{u}_2 = \varepsilon) + \frac{1}{2}U(\tilde{P}_2|\tilde{u}_1 = \eta, \tilde{u}_2 = -\varepsilon) \right] + (1-z)(1-\pi_u) \left[\frac{1}{2}U(\tilde{P}_2|\tilde{u}_1 = -\eta, \tilde{u}_2 = \varepsilon) + \frac{1}{2}U(\tilde{P}_2|\tilde{u}_1 = -\eta, \tilde{u}_2 = -\varepsilon) \right] \geq U(P_0), \quad (A1')$$

which, using Equation (2) and the definition of $\tilde{P}_2$, becomes

$$z\left[\pi_u U\left(V + \eta - \frac{q}{q+z}\varepsilon\right) + (1-\pi_u)U\left(V - \eta - \frac{q}{q+z}\varepsilon\right)\right] + \frac{1-z}{2}\{\pi_u[U(V + \eta + \varepsilon) + U(V + \eta - \varepsilon)] + (1-\pi_u)[U(V - \eta + \varepsilon) + U(V - \eta - \varepsilon)]\} \geq U(P_0).$$

The company will set the offer price at the highest level consistent with participation by the uninformed investors in the IPO, that is, will choose P_0 so that this condition holds with equality. This implies that condition (A3) concerning informed investors is satisfied, since $U(P_0)$ is an average of its left-hand and right-hand side expressions, with weights π_u and $1 - \pi_u$. It follows that, as under risk neutrality, $\pi_u = \lambda/(1 - \lambda)$. Using this result in the previous condition taken with equality, we obtain the following condition defining the equilibrium offer price:

$$U(P_0) = z\left[\frac{\lambda}{1+\lambda}U\left(V + \eta - \frac{q}{q+z}\varepsilon\right) + \frac{1}{1+\lambda}U\left(V - \eta - \frac{q}{q+z}\varepsilon\right)\right] + \frac{1-z}{2}\left\{\frac{\lambda}{1+\lambda}[U(V + \eta + \varepsilon) + U(V + \eta - \varepsilon)] + \frac{1}{1+\lambda}[U(V - \eta + \varepsilon) + U(V - \eta - \varepsilon)]\right\} \quad (A4)$$

Taking a second-order Taylor-series approximation of the right-hand side and collecting terms, one can rewrite expression (A4) as

$$U(P_0) \approx U(V) - U'(V)\left(\frac{1-\lambda}{1+\lambda}\eta + z\frac{q}{q+z}\varepsilon\right) + \frac{U''(V)}{2}\left\{z\left[\eta^2 + \left(\frac{q}{q+z}\varepsilon\right)^2 + 2\frac{1-\lambda}{1+\lambda}\frac{q}{q+z}\eta\varepsilon\right] + (1-z)(\eta^2 + \varepsilon^2)\right\}. \quad (A4')$$

and, collecting terms and recalling that the spread's bid-side portion $S_B = [q/(q+z)]\varepsilon$:

$$U(P_0) \approx U(V) - U'(V)\left(\frac{1-\lambda}{1+\lambda}\eta + zS_B\right) + \frac{U''(V)}{2}\left[\eta^2 + (1-z)\varepsilon^2 + z\left(S_B^2 + 2\frac{1-\lambda}{1+\lambda}\eta S_B\right)\right],$$

which yields Equation (15) through the steps explained in the text. Of course, no approximation is required if the utility function is quadratic.

Derivation of equation (17)

For brevity, in this case to determine the equilibrium price P_0 we concentrate on the participation condition of uninformed investors. Based on Equation (A1), these investors bid if

$$\begin{aligned}
 z \frac{\pi_u}{2} [U(\tilde{P}_1^B | \tilde{u}_1 = \eta, \tilde{q} = q_H) + U(\tilde{P}_1^B | \tilde{u}_1 = \eta, \tilde{q} = q_L)] \\
 + z \frac{1 - \pi_u}{2} [U(\tilde{P}_1^B | \tilde{u}_1 = -\eta, \tilde{q} = q_H) + U(\tilde{P}_1^B | \tilde{u}_1 = -\eta, \tilde{q} = q_L)] \\
 + (1 - z) \frac{\pi_u}{2} [U(\tilde{P}_2 | \tilde{u}_1 = \eta, \tilde{u}_2 = \varepsilon) + U(\tilde{P}_2 | \tilde{u}_1 = \eta, \tilde{u}_2 = -\varepsilon)] \\
 + (1 - z) \frac{1 - \pi_u}{2} [U(\tilde{P}_2 | \tilde{u}_1 = -\eta, \tilde{u}_2 = \varepsilon) + U(\tilde{P}_2 | \tilde{u}_1 = -\eta, \tilde{u}_2 = -\varepsilon)] \geq U(P_0).
 \end{aligned} \tag{A5}$$

Taking this condition with equality, substituting the conditional values of $\tilde{P}_1^B$ and $\tilde{P}_2$ for this case and setting $\pi_u = \lambda/(1 - \lambda)$, one obtains the following condition for the equilibrium offer price P_0 :

$$\begin{aligned}
 U(P_0) = & \frac{z}{2} \frac{\lambda}{1 + \lambda} \left[U\left(V + \eta - \frac{q_H}{q_H + z} \varepsilon\right) + U\left(V + \eta - \frac{q_L}{q_L + z} \varepsilon\right) \right] \\
 & + \frac{z}{2} \frac{1}{1 + \lambda} \left[U\left(V - \eta - \frac{q_H}{q_H + z} \varepsilon\right) + U\left(V - \eta - \frac{q_L}{q_L + z} \varepsilon\right) \right] \\
 & + \frac{1 - z}{2} \left\{ \frac{\lambda}{1 + \lambda} [U(V + \eta + \varepsilon) + U(V + \eta - \varepsilon)] + \frac{1}{1 + \lambda} [U(V - \eta + \varepsilon) + U(V - \eta - \varepsilon)] \right\}.
 \end{aligned} \tag{A6}$$

Taking a second-order Taylor-series approximation of the right-hand side and collecting terms, one can rewrite expression (A6) as

$$\begin{aligned}
 U(P_0) \approx & U(V) - U'(V) \left[\frac{1 - \lambda}{1 + \lambda} \eta + \frac{z}{2} \left(\frac{q_H}{q_H + z} + \frac{q_L}{q_L + z} \right) \varepsilon \right] \\
 & + \frac{U''(V)}{2} \left\{ \eta^2 + \frac{z}{2} \left[\left(\frac{q_H}{q_H + z} \right)^2 + \left(\frac{q_L}{q_L + z} \right)^2 \right] \varepsilon^2 + (1 - z) \varepsilon^2 + z \frac{1 - \lambda}{1 + \lambda} \left(\frac{q_H}{q_H + z} + \frac{q_L}{q_L + z} \right) \eta \varepsilon \right\}
 \end{aligned} \tag{A6'}$$

or using $E(\tilde{S}_B) = \frac{1}{2} [q_H/(q_H + z) + q_L/(q_L + z)] \varepsilon$ and $E(\tilde{S}_B^2) = \frac{1}{2} [(q_H/(q_H + z))^2 + (q_L/(q_L + z))^2] \varepsilon^2$:

$$\begin{aligned}
 U(P_0) \approx & U(V) - U'(V) \left(\left(\frac{1 - \lambda}{1 + \lambda} \eta + z E(\tilde{S}_B) \right) + \frac{U''(V)}{2} [\eta^2 + (1 - z) \varepsilon^2] \right. \\
 & \left. + \frac{U''(V)}{2} z \left\{ \text{Var}(\tilde{S}_B) + (E(\tilde{S}_B))^2 \right\} + 2 \frac{1 - \lambda}{1 + \lambda} \eta E(\tilde{S}_B) \right\},
 \end{aligned}$$

which yields Equation (17) through steps similar to those explained in the text for the derivation of Equation (15).

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