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Thesis title: *Essays in Empirical Finance*

PhD in *Economics and Finance*
Cycle *26th*
Candidate's tutor *Professor Barbara Rindi*
Year of thesis defence *2016*

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discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
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Contents

1. Chapter 1: Do Firms Hedge Their Labor Costs? 1

2. Chapter 2: Tick Size: Theory and Evidence 51

3. Chapter 3: Sub-Penny and Queue-Jumping 123

Tesi di dottorato "Essays in Empirical Finance"
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List of Figures

Chapter	1	
1	Graphical Representation of Difference-in-Differences Analysis	36
Chapter	2	
2	Extensive form of the game	112
3	LM –> SM - Liquid and Illiquid Book	122
Chapter	3	
4	Broker Dealers' β-thresholds	162
5	Public Limit Order Book	163
6	Trading Strategies at t_2	164
7	Order Flows and Market Quality	165
8	NASDAQ queue-jumping and mid-crossing versus stock price	166
9	NYSE queue-jumping and mid-crossing versus stock price	167
10	NYSE distribution of Sub-Penny (including mid-crossing)	168
11	Density Representation for bid price	169

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
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La tesi è tutelata dalla normativa sul diritto d'autore(Legge 22 aprile 1941, n.633 e successive integrazioni e modifiche).
Sono comunque fatti salvi i diritti dell'università Commerciale Luigi Bocconi di riproduzione per scopi di ricerca e didattici, con citazione della fonte.

List of Tables

Chapter 1

1	Variable Definition	36
2	MARA: Descriptive Statistics and Univariate Difference-in-Differences Analysis	37
3	MARA and Cash Holdings	38
4	MARA and Cash Holdings: Robustness Tests	39
5	MARA and Cash Holdings: Placebo Tests	40
6	Model Calibration	41
7	Model: Cash and Mobility	42
8	Descriptive Statistics	43
9	Upstate and downstate hedging	44
10	The effect of labor mobility on cash flow volatility	45
11	The effect of labor mobility on cash holdings	46
12	The effect of labor mobility on cash holdings: Labor Intensity	47
13	The effect of labor mobility on the logarithm of cash holdings	48
14	Cash Holdings and Labor Mobility: Robustness	49

Chapter 2

15	Order Submission Strategy Space	113
16	Price Grids	114
17	LM	115
18	SM	116
19	LSE Group definitions	117
20	RDD: 500 GBX	118

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
La tesi è tutelata dalla normativa sul diritto d'autore(Legge 22 aprile 1941, n.633 e successive integrazioni e modifiche).
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21 LSE Stocks 119

22 RDD - Nasdaq Stocks: Bid Depth, Quoted and Relative Spread 120

23 Nasdaq and NYSE sample. BBO Depth 121

Chapter 3

24 Price Grid 169

25 Order Submission Strategy Space 170

26 Price improvement calculation 171

27 Queue-jumping and Mid-crossing: Spread and Depth 172

28 Queue-jumping and Mid-crossing: Price 173

29 Queue-jumping and Mid-crossing: Depth and Share Volume 174

30 Queue-jumping and Mid-crossing: Quoted and Relative Spread 175

31 Queue-jumping and Mid-Crossing: Depth and Share Volume (Robustness) 176

32 Queue-jumping and Mid-Crossing: Quoted and Relative Spread (Robustness) 177

33 Queue-jumping and Mid-Crossing: Depth and Share Volume (Robustness) 178

34 Queue-jumping and Mid-Crossing: Quoted and Relative Spread (Robustness) 179

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
La tesi è tutelata dalla normativa sul diritto d'autore(Legge 22 aprile 1941, n.633 e successive integrazioni e modifiche).
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Acknowledgements

I would like to express my special appreciation and thanks to my advisor Barbara Rindi, for her continuous support during my PhD and for having initiated me to high-quality academic research. I would thank also Professor Carlo Favero, for his precious guidance from my first year of PhD, Professor Ingrid M. Werner, invaluable mentor who gave me the opportunity to visit the Fisher College of Business at The Ohio State University, and Professor Xiaoji Lin for insightful talks on my job market paper.

I would also like to thank my parents, Giancarlo and Luisella, for endless support, Roberto Steri, for continuous encouragement, and my friends, who shared the path with me.

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Abstract

This thesis deals with the concept of liquidity in a broad sense. First, I analyze the liquidity from the point of view of the firm. Second, I focus on the liquidity in a public limit order book, so taking a market microstructure perspective.

In Chapter 1, "Do Firms Hedge Their Labor Costs?", I document that firms hold cash to hedge their labor costs. First, I exploit a negative shock to labor mobility, the Michigan Antitrust Reform Act, to show that firms in Michigan reduce their cash holdings by 15% in a difference-in-differences setting. Second, I rationalize this finding in an industry equilibrium model where firms make hiring and firing decisions, as well as liquidity management decisions, in the presence of a mobile workforce. In the model, cash is a valuable alternative to costly external financing to cover volatile wage bills, hiring, and firing costs. Using a large sample of U.S. firms, by means of calibration, I generate a broad set of quantitative and empirical predictions that find strong support in the data. Specifically, I find that one standard deviation increase in labor mobility is associated with a 10% increase in firms' cash holdings. Approximately two thirds of this figure is due to mobility within the same industry, and one third to mobility to other industries.

In Chapter 2, "Tick Size: Theory and Evidence" (with Ingrid M. Werner, Yuanji Wen, Barbara Rindi and Sabrina Buti), we model a public limit order book where rational traders decide whether to demand or supply liquidity, and where liquidity builds endogenously. The model predicts that a reduction of the tick size will cause spreads and welfare to deteriorate for illiquid but improve for liquid books. We find empirical support for these predictions based on European and U.S. data. The model also generates predictions for volume, but we find less empirical support for these predictions which we attribute to opportunistic High-Frequency-Traders selectively entering the market.

In Chapter 3, "Sub-Penny and Queue-Jumping" (with Ingrid M. Werner, Yuanji Wen, Barbara Rindi and Sabrina Buti), we develop a model where a public limit order book (PLB) competes with a Sub-Penny Venue, which allows Sub-Penny Trading (SPT). SPT occurs when a trader undercuts orders in the PLB by less than one penny, a practice we call queue jumping (QJ). QJ is higher for NASDAQ than for NYSE stocks. We confirm the model's predictions that QJ increases in liquidity and in the tick-to-price ratio. We also find that QJ is associated with improved PLB market quality, especially for large capitalization stocks. Finally, we show that High Frequency Trading is negatively related to QJ.

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Chapter 1

Do Firms Hedge Their Labor Costs?

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Do Firms Hedge Their Labor Costs?

Francesco Consonni *

JOB MARKET PAPER

November 2015

Abstract

I document that firms hold cash to hedge their labor costs. First, I exploit a negative shock to labor mobility, the Michigan Antitrust Reform Act, to show that firms in Michigan reduce their cash holdings by 15% in a difference-in-differences setting. Second, I rationalize this finding in an industry equilibrium model where firms make hiring and firing decisions, as well as liquidity management decisions, in the presence of a mobile workforce. In the model, cash is a valuable alternative to costly external financing to cover volatile wage bills, hiring, and firing costs. Using a large sample of U.S. firms, by means of calibration, I generate a broad set of quantitative and empirical predictions that find strong support in the data. Specifically, I find that one standard deviation increase in labor mobility is associated with a 10% increase in firms' cash holdings. Approximately two thirds of this figure is due to mobility within the same industry, and one third to mobility to other industries.

Keywords: cash, corporate liquidity, labor, mobility, hedging

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I thank my thesis committee and foremost Carlo Favero. I am gratefully indebted to Ingrid M. Werner, who supported and encouraged me during my stay at The Ohio State University. I also thank Xiaoji Lin for useful and insightful talks. I owe special thanks to Roberto Steri for the incredible amount of time and support in all stages of this work. I am also grateful to Itzhak (Zahi) Ben-David, Nicola Gennaioli, Fabiano Schivardi, Nicolas Serrano-Velarde, Hannes Wagner, Michael Weisbach and partecipants to Bocconi Brown Bag seminars. All the errors are my own.

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1.1 Introduction

According to the U.S. Internal Revenue Service, labor costs represent a substantial share of firms' costs, up to 30% of sales. According to the Job Openings and Labor Turnover Survey (JOLTS), annual separation rates in the U.S., measured as the ratio of total separations during the entire year to total employment, are as high as 40%.[1] Workers' mobility, both towards other industries and towards other firms in the same industry, renders labor costs volatile. On the demand side, workers are willing to move between different jobs and occupations. On the supply side, firms adjust their labor force to maximize their profits in the presence of costly hiring and firing. Overall, firms are making both hiring and firing decisions in the presence of a mobile workforce, volatile wage bills, and costly labor adjustments. In this setting, for example, a financially constrained firm may optimally decide to reduce current production and payouts to hoard cash to finance future wage bills and train new hires. A natural question therefore arises: do firms hold cash to hedge their labor costs?

I first provide novel empirical evidence that cash holdings shrink after the mobility of employees is reduced. In particular, I exploit an inadvertent policy reversal in Michigan in 1985, when the Michigan Antitrust Reform Act (MARA) repealed the ban on agreements not to compete for employees. Several studies document that mobility decreases once non-competes begin to be enforced.[2] Thus, I use the enforcement of agreements not to compete as an exogenous shock to labor mobility. In a difference-in-differences setting, I show that, after MARA was enacted, firms in Michigan reduced their cash-to-assets ratio by about 15% taking U.S. states that continued to restrict the use of non-competes as a benchmark. This result is robust to alternative explanations. First, I control for the possibility for high R&D firms to reduce their cash holdings after MARA due to an increase in their borrowing capacity. Specifically, the reform may guarantee a better protection of firms' intangible capital, that can be pledged as collateral, potentially reducing the need for savings. Second, I control for the nature of Michigan's economy, at that time dominated by the automotive industry. In fact this feature might lead to a peculiar response to MARA. Third, extant studies (Fresard, 2010, Morellec, Nikolov and Zucchi, 2013) establish a link between cash holdings and product market competition. This suggests that the antitrust aspect of MARA, namely the reduction of price-fixing and collusion, might affect the competitive environment and, accordingly, firms' liquidity policies. To

[1] Total separations include both voluntary quits and involuntary layoffs (JOLTS).

[2] See, for example, Fallick, Fleischman and Rebitzer (2006), Marx, Strumsky and Fleming (2009), Garmaise (2009).

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mitigate this concern I implement placebo tests on two states, Delaware and Texas, that engaged in antitrust reforms in the same decade of MARA without modifying regulation on non-competes. In these states, I find no evidence of reductions in cash holdings after the reforms.

Albeit limited in scope, the aforementioned natural experiment suggests that firms hedge labor mobility and its associated costs using cash holdings. To rationalize the economic mechanism underlying this empirical evidence, I propose an industry equilibrium model where firms make hiring and firing decisions, as well as liquidity management decisions, in the presence of a mobile workforce. The model allows to assess the quantitative importance of labor cost hedging for the universe of U.S. listed firms, and to produce new testable predictions. In the model, workforce mobility generates from the comparison of the expected future performance of the firm and other firms, both in the same industry (within-industry mobility) and in other industries (between-industry mobility). When a firm's expected performance decreases in comparison to its competitors, the firm becomes a less attractive employer and experiences an outflow of workers. Symmetrically, when the firm is expected to be more profitable than competitors, it attracts more workers. Firms' hiring and firing decisions are subject to adjustment costs which capture, for example, advertising, recruitment, selection, training, and decreased productivity.[3] In this framework, workers' mobility drives the economic trade-off between the costs of adjusting the labor force, and the profits from choosing a labor input that better responds to market conditions. For example, if twenty workers leave but a firm optimally reduces its current labor force by only ten workers, it trades off a lower production in the next period and hiring costs to counteract this outflow of workers. Firms also make liquidity management decisions. Cash holdings are valuable because savings represent an alternative to costly external financing for covering labor costs in the presence of mobility. Thus, cash serves as a hedging device. In the model, two types of hedging needs can be distinguished: downstate hedging and upstate hedging. The former refers to firms holding cash to pay wage bills and firing costs during downturns. The latter refers to firms holding cash to entertain growth opportunities in good times and cover the associated hiring costs.

I solve the model numerically, and by means of calibration I quantify both the amount of cash firms use to hedge labor costs associated to workers' mobility, and the relative importance of upstate and downstate hedging. My quantitative results refer to a large sample of Compustat firms for the period 1988-2011. Under the baseline calibration, I simulate the behavior of a large number of firms and, by regressing cash

[3]Kuehn, Simutin and Wang (2014).

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holdings on mobility, I show that one standard deviation increase in labor mobility is associated with a 10% increase in firms' cash holdings. Approximately two thirds of this figure is due to mobility within the same industry, and one third to mobility to other industries. Furthermore, I show that upstate hedging is quantitatively more important than downstate hedging in my sample. In particular, I regress the change in cash holdings on the change in total factor productivity, which captures profitability at the firm level, both on real and simulated data. When profitability increases, a firm is exposed to persistent growth opportunities and cash can be valuable to hire new workers and pay future wage bills (upstate hedging). Similarly, when profitability is decreasing, internally generated profits do not suffice to pay wage bills, and cash savings can serve this purpose (downstate hedging). Regressions on simulated data uncover patterns that are consistent with those in the data. Empirically, my results are robust to the inclusion of standard determinants of changes in cash holdings.[4]

To further investigate the relationship between firms' liquidity management decisions and labor mobility, using my model, I develop different testable predictions by means of sample splits and comparative statics. In particular, I consider two groups of predictions. The first one relates to the different hedging behavior of capital intensive and labor intensive firms. By splitting my sample into labor intensive and capital intensive firms, I find that downstate hedging is typical of labor intensive firms, while upstate hedging is associated to the optimal liquidity policy of capital intensive firms. This is consistent with the predictions of the model: labor intensive firms need cash to pay wage bill during downturns, while capital intensive firms use cash to seize growth opportunities and associated hiring costs in good times. The second set of predictions concerns the effects of labor mobility on cash flow volatility and cash holdings. To study these relations, I employ a measure of labor mobility in line with Donangelo (2014), constructed from the dispersion of occupations across industries. This measure is therefore a proxy of between-industry mobility. Consistently with the predictions of the model, both cash flow volatility and cash holdings are positively related to labor mobility. Labor mobility exacerbates firms' hedging needs by adding volatility to firms' cash flows. In particular, I document that one standard deviation in labor mobility is associated to a 2% increase in the cash-to-assets ratio. The effect of labor mobility on cash holdings is stronger for financially constrained firms, defined using size, payout ratios, and the Whited and Wu's index. This suggests the presence of a precautionary savings motive. My results are robust across different specifications and they hold after controlling for a host of variables. Specifically, I

[4]For a description of determinants of changes in cash holdings see, for example, Almeida, Campello and Weisbach (2004).

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also include union coverage, which relates to labor mobility (Chen, Kacperczyk and Ortiz-Molina, 2011) and it has been proved to impact also cash holdings (Klasa, Maxwell and Ortiz-Molina, 2009).

My paper relates to three different lines of literature. First, it adds to the growing literature examining the interaction between labor and capital structure, both empirically (Kuzmina, 2013, Schmalz, 2013, Serfling, 2013, Simintzi, Vig and Volpin, 2014, Ghaly, Dang and Stathopoulos, 2015) and theoretically (Quadrini and Sun, 2013, Michaels, Page and Whited, 2014). Unlike previous studies, I focus on the relationship between labor mobility and corporate liquidity management.[5] Second, my paper complements the literature on the determinants of cash holdings (Opler, Pinkowitz, Stulz and Williamson, 1999, Bates, Kahle and Stulz, 2009). In particular, I focus on the precautionary savings motive in the presence of volatile cash flows due to labor mobility.[6] Finally, this paper relates to the expanding literature which uses dynamic models to examine corporate liquidity choices (Bolton, Chen and Wang, 2011, Byun, Polkovnichenko and Rebello, 2013, Eisfeldt and Muir, 2014, Falato, Kadyrzhanova and Sim, 2013). Concerning the structure of the model and the solution method, my paper is close to Riddick and Whited (2009), DeAngelo, DeAngelo and Whited (2011), Nikolov, Schmid and Steri (2013), and to Zhang (2005) for the industry aggregation procedure.

The paper is organized as follows. Section two presents the natural experiment. Section three describes the model and derives testable hypotheses. Section four presents empirical results. Section five concludes.

1.2 Natural Experiment

I this section, I propose a natural experiment in which the mobility of workers is exogenously reduced. In particular, I use the enforcement of agreements not to compete as a proxy for a shock to labor mobility. In this way I can study the effect of a reduction of workers' mobility on cash holdings.

Turning to the description of the event, I exploit an inadvertent Michigan policy reversal which re-introduced the agreement not to compete for employees. In this case, I am dealing with a reduction in mobility due to a state law. Non-competes are not governed by a federal statute. Non-compete enforcement in Michigan had

[5]The concept of labor mobility has also been used in the finance literature in relation to asset prices (Donangelo, 2014, Kuehn, Simutin and Wang, 2014) and corporate diversification (Tate and Yang, 2015).

[6]In the literature, other examples of source of cash flow riskiness are competition (Morellec, Nikolov and Zucchi, 2013) and demographic demand shifts (Cunha and Pollet, 2014)

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long been governed by Public Act No. 329 of 1905. This Act prohibited the use of non-competes until 1985, when the Michigan Antitrust Reform Act (MARA) was passed. MARA indeed repealed the ban on agreement not to compete. According to law literature (Hyde, 2003) agreements not to compete reduce the mobility of workers. In the finance literature Garmaise (2009) finds that increased enforceability of agreements not to compete reduce executive mobility. While Fallick, Fleischman and Rebitzer (2006) show that unenforceability of non compete agreements under California state law enhances mobility in IT clusters. Marx, Strumsky and Fleming (2009), controlling for changes in the auto industry central to Michigan's economy, find that the enforcement of non-competes indeed attenuates mobility. Moreover, non-compete enforcement decreases mobility more sharply for inventors with firm-specific skills and for those who specialize in narrow technical fields. Marx, Strumsky and Fleming (2009) focus on inventor mobility using a measure based on U.S. patents. They find that inventor mobility decreases after the introduction of agreements not to compete. Furthermore, according to Wall Street Journal (2013), after 20 years from the repeal of the ban, agreements not to compete are still widespread and effective, reducing mobility in Michigan. Finally, according to a panel of lawyers, in Michigan, the threat of a non-compete lawsuit is too often enough to scare an individual to take the sidelines and sit idle for a year or two until a non-compete runs out (i.e., "career detours"). As for the exogeneity of the shock, according to lawyers active in Michigan at the time MARA was passed, the repeal of the ban of non competes was basically unexpected. All of a sudden the lawyers realized that agreement not to compete were no more prohibited.

The empirical design is based on a difference-in-differences (DiD) method. According to MARA, covenants and agreements were affected if entered into after March 29, 1985. Hence, the first year of treatment is 1986. The sample includes firm-level data from Compustat for the period 1976 - 1995, a symmetric window with respect to the year of the introduction of MARA. The firms are from Michigan, the treated unity, and from a set of states which did not enforce agreement not to compete in a period close to MARA. They are Alaska, California, Connecticut, Minnesota, Montana, North Dakota, Nevada, Oklahoma, Washington, and West Virginia (Stuart and Sorenson, 2003) and they represent the control group. To assess state affiliation I use the location of the headquarters, the place where the firm is supposed to do business, and not the state of incorporation. The location is retrieved from the ZIP code reported in Compustat and historical moves between states are corrected using the table of corporate moves in Compustat. Firms which changed states during the period of the analysis are excluded along with firms from regulated

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industries (SIC 4900-4999) and financial industries (SIC 6000-6999). The final sample consists in 14,571 firm-year observations. The dependent variable is the sum of cash and cash equivalents deflated by total asset. In the analysis I also employ standard determinants of cash holdings, whose description can be found in Table 2. Table 3 Panel A reports the summary statistics of the variables.

For the correct estimation of the effect of labor mobility on cash holdings, the comparability assumption (i.e., the parallel trend assumption) is crucial since, after the perturbation, the control group is used to infer the counterfactual level of cash holdings (Angrist and Pischke, 2008). To test this assumption, in Figure 1, I plot the average values of cash holdings in the treatment and control groups. Before the introduction of MARA, the parallel trend assumption seems satisfied. The plots suggests that, before the introduction of MARA, there was a parallel trend of cash holdings between Michigan and control states. After the introduction of MARA, the two series started diverging consistently with the idea that a reduction of labor mobility is associated with less need for cash for precautionary savings motive.

[Insert Figure 1 about here]

This preliminary intuition is confirmed by the univariate difference-in-differences analysis reported in Table 3 Panel B. While for control states the cash holdings steadily increase, for Michigan they are substantially unchanged. The DiD effect is statistically significant and it amounts to -5.5%.

[Insert Table 3 about here]

I then move to a regression analysis. The dependent variable is the sum of cash and cash equivalents deflated by total asset. Among the covariates, I have the treatment unit variable, $Michigan$, a dummy which is equal to one if the headquarter of the firm is located in Michigan. The variable $after$ is a dummy variable which is equal to one for all years following 1986 (included). Finally, to identify the treatment effect, I introduce the interaction variable $Michigan * after$. I also introduce as controls a set of standard determinants of cash holdings (Opler, Pinkowitz, Stulz and Williamson, 1999 and Bates, Kahle and Stulz, 2009).

I estimate the following model:

$$cash_{i,t} = \beta_1 Michigan_i + \beta_2 after_i + \beta_3 Michigan_i * after_i + \gamma X_{i,t} + \theta_t + \mu_j + \varepsilon_{i,t} \quad (1)$$

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The subscripts i, t refer to firm and year, respectively. $X_{i,t}$ is a standard set of controls at firm level, θ_t are the year fixed effects and μ_j are the industry fixed effects. I estimate different specifications of the model. For the basic analysis, I exclude covariates $X_{i,t}$ and the fixed effects. I then run a specification including covariates $X_{i,t}$ and, finally, I run the full specification of model (1). Standard errors are clustered by firm for all specifications. I am primarily interested in statistical and economic significance of coefficient β_3, which represents the treatment effect. Results are reported in Table 4. The coefficient on the treatment effect in the Column 1 of Table 4 is consistent with the DiD effect reported in Table 3 Panel B. Across all specifications, the treatment effect ranges from -0.055 to -0.020 suggesting that the introduction of agreement not to compete partially reduced the cash holdings of Michigan firms with respect to firms in control states. Taking the most conservative estimate (β_3 = -0.020) if, on average, Michigan firms used to have 13% of cash holdings pre-MARA (Table 3 Panel B) after MARA was enacted, those firms reduced their cash holdings by about 15% (-0.02/0.13) when benchmarked against firms in control states.

Having assessed the treatment effect, I turn to robustness and placebo tests.

[Insert Table 4 about here]

Robustness Tests

Michigan is well-known for its automotive industry which can hence affect the results. In particular, as pointed out in Singleton (1992), oil shocks can have affected the automotive industry. Even though year fixed effects have already been introduced, I add the following controls to the full model (1) $Michigan * Auto$, $After * Auto$ and $Michigan * After * Auto$, where $Auto$ is a dummy which is equal to one if the firm belongs to the automotive industry (i.e., SIC code 3710). I also estimate the model separately for R&D and not R&D firms, where a firm is classified as R&D if it reports positive R&D expenditures. The reason for this sample split relies on the fact that cash holdings are affected by a trend and intangible capital has been identified as a main driver of this secular rise (Falato, Kadyrzhanova and Sim, 2013). Furthermore, with this sample split, I also account for an alternative explanation related to the "value of secrecy" (Younge and Marx, 2013). Indeed, the effect that I find is not driven by R&D firms. I then repeat the analysis using a narrower window (5 year before and 5 after the introduction of MARA). I also use as control group all the states. Finally I take the logarithm of the dependent variable to take into account outliers. Across all robustness checks, the coefficient of the treatment effect remains negative and significant, both statistically and economically. Results are

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reported in Table 5.

[Insert Table 5 about here]

Placebo Tests

The stated purpose of the regulation was to increase competition. Competition in the product markets generally leads to higher cash holdings for firms (Morellec, Nikolov and Zucchi, 2013). So, to this extent, the competition effect should drive to an increase in cash holdings. To further investigate whether the antitrust aspects of MARA, namely reduction of collusion and price-fixing, can have affected the results, I run placebo tests using two states which underwent antitrust reforms in a period close to MARA: Delaware and Texas. Delaware passed the Delaware Antitrust Act of 1980 and Texas enacted the Texas Free Enterprise and Antitrust Act of 1983. I run a regression analysis following the previous methodology and using as control group all U.S. states. For Delaware, I find that the interaction term is positive and statistically significant hinting that the antitrust aspects of that reform were sensible, consistent with theories on cash holdings and competition. For Texas, I do not find any statistical significance. Taken together, these two placebo tests suggest that the antitrust effect of MARA alone are unlikely to have driven the results. Results are reported in Table 6.

[Insert Table 6 about here]

A tentative explanation of the reported evidence is the following. When labor mobility is reduced, firms' cash flows are less risky and hence firms have less need for cash. In the next section , I rationalize the mechanism in a model.An alternative explanation, untested, is that firms hold less cash because the risk that they are going to lose their human capital, in particular the skilled high-educated one, is reduced. Klasa, Ortiz-Molina, Serfling and Srinivasan (2014) indeed show that the risk of losing intellectual property affects a firm's default risk.

In this section, I provided new evidence that labor mobility can affect the liquidity management of a firm. In particular, I show that firms hold less cash when facing less mobile workers. To better investigate the mechanism and quantify the effects, in the next section I propose an industry model which entails two types of mobility: within and between industry. In the proposed natural experiment, I can not distinguish between the two types of mobility. However, as reported by the OECD Employment Outlook 2009, both types matter. To spot the difference between within industry and across industry mobility, consider the following examples. Take into account

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an IT guy working for a small and promising high-tech start-up. After the burst of dot-com bubble, he was likely to relocate himself in a different industry being still involved in IT (e.g., managing the patients' database of an hospital). Take a similar IT guy, 10 years later, working for a similar high-tech start-up. Google notices him and makes an outstanding offer. He accepts and moves. This is mobility within the same industry (i.e., IT).

1.3 Model

To analyze labor mobility and firm's cash accumulation decisions. I construct a neoclassical industry equilibrium model with aggregate uncertainty. I need an industry model to translate the fact that labor mobility can be both within and between industry. The industry is composed of a continuum of competitive firms which produce a homogeneous good. Firms behave competitively and take the price in the product market as given.

1.3.1 Technology

Production requires one input, labor n, and it is subject to both an aggregate shock, x, and an idiosyncratic shock, z. The variable x_t is the aggregate productivity shock and has a stationary and monotone Markov transition function, denoted by $Q_x(x_{t+1}|x_t)$. The law of motion of x_t is defined as follows:

$$x_{t+1} = \mu_x(1-\rho_x) + \rho_x x_t + \sigma_x \varepsilon^x_{t+1} \tag{2}$$

The variable z_t is the idiosyncratic productivity shock and has a stationary and monotone Markov transition function, denoted by $Q_z(z_{t+1}|z_t)$. The law of motion of z_t is defined as follows:

$$z_{i,t+1} = \rho_z z_{i,t} + \sigma_z \varepsilon^z_{i,t+1} \tag{3}$$

Where ε^x_{t+1} and $\varepsilon^z_{i,t+1}$ are IID standard normal shocks and $\varepsilon^z_{i,t+1}$ and $\varepsilon^z_{j,t+1}$ are uncorrelated for any pair (i,j) with $i \neq j$. Furthermore, ε^x_{t+1} is independent of $\varepsilon^z_{i,t+1}$ for all i. The parametrizations in equations (2) and (3) ensure that the transition probabilities have the Feller property.

Both aggregate and idiosyncratic shocks are required to capture the feature of labor mobility. I need an aggregate shock to capture the between-industry labor mobility (i.e., workers may leave/enter the industry depending on the aggregate

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performance of the industry). I also need an idiosyncratic shock to allow the worker to leave an unproductive firm and move to a competitor in the same industry.

Production requires one input, labor n. At period t I have then:

$$y_{i,t} = e^{x_t + z_{i,t}} n_{i,t}^{\alpha} - wg_{i,t} n_{i,t}$$

where $0 < \alpha < 1$. The production technology displays decreasing returns to scale. $y_{i,t}$ is the operating income and $n_{i,t}$ is the labor stock of firm i at time t. wg_t is the wage rate which is correlated with the two shocks and it is given by (e.g. Belo, Lin and Bazdresch, 2014):

$$wg_{i,t} = wg_1 e^{wg_2(x_t + z_{i,t})}$$

where $wg_1 > 0$ and $0 < wg_2 < 1$. In this specification, $wg_1$is a scaling factor and the constraint $0 < wg_2 < 1$ allows me to capture the empirical fact that the real wages rate is less volatile than output as well as some procyclicality of the real wage rate, as reported in Favilukis and Lin (2014) and Belo, Lin and Zhao (2015) and Belo, Lin and Bazdresch (2014) in U.S. data.

1.3.2 Industry demand

I denote the inverse demand function $P(Y_t)$, where P_t is the output price and Y_t is the total output in the industry at time t. In line with Caballero and Pindyck (1996) and Zhang (2005), I parametrize $P(.)$ as

$$P(Y_t) = Y_t^{-\eta}$$

where $0 < \eta < 1$ and I can interpret $1/\eta$ as the price elasticity of demand.

1.3.3 Firms

Firms make optimal decisions after observing the shocks at the beginning of the period t.

Value Maximization

The firm's operating income in period t is determined by its labor stock at the beginning of the period, n_t, aggregate shock x_t, idiosyncratic shock z_t and log output price $p_t \equiv logP_t$. I suppress the firm index i for notational simplicity. The operating income is

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$$\pi_t = \pi(n_t, z_t; x_t, p_t) = (1-\tau)(e^{x_t+z_t+p_t} n_t^{\alpha} - w g_t n_t)$$

where $0 < \tau < 1$is the corporate tax rate. Labor stock accumulates according to the rule

$$n_{t+1} = h_t n_t + (1-s) n_t + m(z_{t+1}; x_{t+1}) n_t \tag{4}$$

where h_t is the gross hiring rate, s is the separation rate, which captures small probability events like retirement, death, and disability, and $m(z_t; x_t)$ is the mobility rate, which captures the major part of voluntary flows and it is related to firms' performance. In fact, workers are willing to switch jobs mainly for reasons of career development, better pay or preferable working conditions.[7] The mobility rate is defined as

$$m(z_{t+1}; x_{t+1}) \equiv \beta_z [E_t(z_{t+1}|z_t) - E(z_{t+1})] + \beta_x [E_t(x_{t+1}|x_t) - E(x_{t+1})]$$

where $\beta_z > 0$ and $\beta_x > 0$ are the sensitivities to the idiosyncratic and aggregate components of the mobility rate, respectively. The intuition behind this functional form is twofold. First, the mobility rate depends on both idiosyncratic and aggregate productivity shocks, to embed both the within-industry and between-industry mobility dimensions. Second, mobility arises from the expected performance of the firm and the industry when benchmarked against the average performance of others firms and industries. The average profitability of other firms and other industries (i.e., the benchmark), is represented by the unconditional value of the idiosyncratic and aggregate shocks, respectively. When the performance of a firm is expected to be relatively high with respect to other firms in the same industry (i.e., $E_t(z_{t+1}|z_t) > E(z_{t+1})$), it attracts more workers. Symmetrically, when the expected performance of a firm is relatively low (i.e., $E_t(z_{t+1}|z_t) < E(z_{t+1})$), it is less attractive and hence it experiences an outflow of workers. This definition entails both a cross-sectional dimension, given by the average performance used as benchmark, and a time-series dimension. As for the latter, in fact, the expected performance of the firm depends on the current state and the associated transition probabilities. Similarly, I can interpret the portion of the mobility rate which attains to industry's performance. The mobility captures all flows which depend on the performance of the firm and of the industry. On top of these potential flows, a firm makes its hiring and firing decisions. In particular, the firm at period t, chooses the gross hiring h_t, which can be both positive and

[7] Kuehn, Simutin and Wang (2014)

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negative. Workers become productive at period $t+1$. Workforce at period $t+1$, n_{t+1}, includes both the gross hiring and the effect of the mobility rate. The mobility rate in expectation is zero, so it does not affect, on average, the level of employment. All flows, related to mobility rate and hiring and firing decisions, are subject to adjustment costs a. The functional form of a is asymmetric and convex:

$$\begin{aligned} a(h_t, n_t) &= \frac{\theta^+}{2}\left(h_t + m_t\right)^2 n_t \chi_{\{h_t+m_t\geq 0 \vee m_t \geq 0\}} + \\ &+ \frac{\theta^+}{2}\left(h_t\right)^2 n_t \chi_{\{h_t\geq 0 \vee m_t \leq 0\}} + \\ &+ \frac{\theta^-}{2}\left(h_t\right)^2 n_t \chi_{\{h_t\leq 0 \vee m_t \leq 0\}} + \\ &+ \frac{\theta^-}{2}\left(h_t + m_t\right)^2 n_t \chi_{\{h_t+m_t\leq 0 \vee m_t \geq 0\}} \end{aligned}$$

and $\chi_{\{.\}}$ is an indicator function which is equal to one when the event in $\{.\}$ is true and zero otherwise. The adjustment costs are asymmetric with $\theta^+ > \theta^-$, to capture the fact that in the U.S., the country of my empirical analysis, hiring is more costly than firing. Albeit not conventional, the functional form captures a very simple intuition. A firm faces potential flows related to its performance (i.e., the mobility effect) and it adjusts these flows with hiring and firing decisions paying costs accordingly, with outflows due to mobility being costless.

Hiring and distributions to shareholders can be financed with internally generated cash flows and external financing. Furthermore, firms can hold cash c_t. Cash balances are held as a one period discount bond. I denote the discount rate r. Holding cash is costly since the firm pays taxes at the rate τ on income. Hence the after-tax interest on cash balance is $r(1-\tau)$. Cash derives value because it is an alternative to costly external financing.

The firm's net payout is given be

$$d(n_t, c_t, z_t, x_t, p_t, n_{t+1}, c_{t+1}) = \pi_t(n_t, z_t; x_t, p_t) + c_t(1 + r(1-\tau)) - c_{t+1} - a(h_t, n_t)$$

When $d(.) > 0$ the firm pays out dividend to investors and when $d(.) < 0$ the firm raises equity. When a firm raises external funds, it faces a financing cost

$$\lambda(d(.)) \equiv (\lambda_0 + \lambda_1 d(.))1_{d<0}$$

where $\lambda_0 \geq 0$ and $\lambda_1 \geq 0$. Since external financing is costly, the firm can find optimal to hoard cash if it anticipates that future cash flow will be negative. In particular, the firm can decide to temporarily have a negative cash flow (e.g.. when

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the productivity is low) and avoid firing thanks to the cash savings.

The current state of the firm can be expressed using a new state variable, the realized net worth

$$w_t \equiv \pi_t(n_t, z_t; x_t, p_t) + c_t(1 + r(1 - \tau))$$

Realized net worth represents the amount of resources that are available to the firm in a certain state (Rampini and Viswanathan, 2013). It is the sum of current cash flows and cash holdings.

The sources and uses of funds identity is then

$$w_t \equiv d(.) + c_{t+1} + a(h_t, n_t)$$

The firm's decision problem amounts at choosing the labor stock and the cash balances to maximize the present value of the payouts to shareholders. By the Bellman principle of optimality the maximization problem can be written recursively

$$V_t(n_t, w_t, z_t; x_t, p_t) = \max_{h_t, c_{t+1}} \left\{ d(.) + \lambda(d(.)) + \frac{1}{1+r} E_t[V_{t+1}(n_{t+1}, w_{t+1}, z_{t+1}; x_{t+1}, p_{t+1})] \right\} \tag{5}$$

subject to the constraints

$$w_t \geq d_t(.) + c_{t+1} + a(h_t, n_t) \tag{6}$$

$$w_{t+1} \leq \pi_{t+1}(n_{t+1}, z_{t+1}; x_{t+1}, p_{t+1}) + c_{t+1}(1 + r(1 - \tau)) \tag{7}$$

$$c_{t+1} \geq 0 \tag{8}$$

Constraint (6) states that the current net worth has to be higher than or equal to the sum of current dividend, the investment in liquid assets and the adjustment costs. Moving forward one period, constraint (7) imposes that the future net worth has to lower than or equal to the internally generated cash flows and the cash holdings in any future state. Finally, constraint (8) represents the non-negativity requirement for cash.

Aggregation

In the previous section, I described the optimization behavior of the firms. Now I characterize the aggregate behavior of the industry. The output price is determined

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discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
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in the competitive equilibrium to equate industry demand and supply in the product market. The industry output and the price depend on the cross-sectional distribution of firms.

I denote μ_t the measure over the labor stock, net worth and idiosyncratic shocks for all the firms in the industry at time t. I denote $h(n_t, w_t, z_t; x_t, p_t)$ and $y(n_t, w_t, z_t; x_t, p_t)$, respectively, the optimal gross hiring and the output of the firm and output for the firm with labor stock n_t, net worth w_t, idiosyncratic productivity z_t operating in an industry characterized by log price p_t and aggregate productivity x_t. I define Ω to be any measurable set in the product space of n, w and z and I denote $\Gamma(\mu_t, x_t, x_{t+1})$ the law of motion for the firm distribution μ_t. Then $\Gamma(\cdot, \cdot, \cdot)$ can be formally defined as

$$\mu_{t+1}(\Omega; x_{t+1}) = T(\Omega, (n_t, w_t, z_t); x_t)\mu_t(n_t, w_t, z_t; x_t) \tag{9}$$

where the operator T is defined as

$$T(\Omega, (n_t, z_t); x_t) \equiv \int\int \chi_{\{(n_{t+1}, w_{t+1}, z_{t+1}) \in \Omega\}} Q_z(dz_{t+1}|z_t) Q_x(dx_{t+1}|x_t) \tag{10}$$

The total industry output can be written then as

$$Y_t = \int y(n_t, w_t, z_t; x_t, p_t)\mu_t(dn, dz) \tag{11}$$

Equilibrium

A recursive equilibrium is characterized by: (1) a log industry output price p_t^*; (2) an optimal hiring rule $h^*(n_t, w_t, z_t; x_t, p_t^*)$, an optimal cash policy rule $c^*(n_t, w_t, z_t; x_t, p_t^*)$, as well as a value function $V^*(n_t, w_t, z_t; x_t, p_t^*)$ for each firm; and (3) a law of motion of firm distribution Γ^*, such that:

- Optimality: $h^*(n_t, w_t, z_t; x_t, p_t^*)$, $c^*(n_t, w_t, z_t; x_t, p_t^*)$ and $V^*(n_t, w_t, z_t; x_t, p_t^*)$ solve the value-maximization problem (5) for each firm;
- Consistency: the aggregate output Y_t is consistent with the production of all firms in the industry, that is, (11) holds. The law of motion of firm distribution Γ^* is consistent with the optimal decisions of the firms, that is (9) and (10) hold.
- Product market clearing

$$e^{p_t^*} = Y_t^{-\eta}$$

Tesi di dottorato "Essays in Empirical Finance"
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1.3.4 Model Solution

Because of the endogeneity of the log output price, which depends on the distribution of firms, the model has to be solved using a recursive procedure (Zhang, 2005). Here I provide a sketch of the algorithm, a detailed description can be found in the Appendix A. Basically, the idea is to use two loops (outer and inner) to overcome the endogeneity of the log output price. The procedure amounts at the following steps: (1) Guess a functional form and a set of parameters for the law of motion of the log output price. (2) Solve the firm's optimization problem given the previous guess. This step entails a value function iteration method and it is briefly described below. (3) Use firm's optimal policy rules to simulate the behavior of N firms over a large number T of periods. (4) Use the stationary region of the simulated data to estimate the parameters of the functional form for the law of motion of log output price. (5) Compute measures of goodness-of-fit. (6) Stop if the estimation gives parameter values which are very close to those in the last iteration and the goodness-of-fit is satisfactory. Otherwise, change the functional form guessed at point (1).

As for the firm optimization problem, the model is solved on a discrete grid by value function iteration. The Bellman operator in equation (5) is indeed a contraction mapping, in that Blackwell's sufficient conditions hold in this framework. Therefore, the fixed point of the functional equation (5) is well-defined. For a standard formal proof in a similar framework, I refer to Hennessy and Whited (2005). This type of problems often carry a computational burden. I deal with it by coding the algorithm in Fortran, which proved to be faster than Matlab.[8]

1.4 Empirical Analysis

1.4.1 Calibration and Identification

The objective of this section is to calibrate the model. Calibration amounts at setting the parameters of the model to match a set of data moments. Calibration serves to assess the quantitative implications of the model and to perform counterfactual comparative statics.

On the production side, the elasticity of the profit function α with respect to labor is set equal to 0.65 in line with Belo and Lin (2012). The inverse price elasticity of demand η is set equal to 0.5. following Caballero and Pindyck (1996) and Zhang (2005). The mean of the aggregate shock, μ_x, and the level wage rate parameter, wg_1, are chosen to match the level of the aggregate productivity in the economy and

[8] In my case, I got an increase in speed of roughly 3 times

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di CONSONNI FRANCESCO
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are set equal to -2 and 0.075. The sensitivity of the wage rate to the productivity shocks, wg_2, is set to 0.1, to capture the feature that real wages are less cyclical than productivity (Belo and Lin, 2012). The persistence, ρ_x, and the standard deviation, σ_x , of the aggregate shock are equal to 0.8 and 0.05, respectively (Steri, 2013). The persistence, ρ_z, and the standard deviation, σ_z , of the idiosyncratic shock are equal to 0.725 and 0.5, respectively, values close to DeAngelo, DeAngelo and Whited (2011). The convex parameters of adjustment costs are chosen so that hiring is more costly than firing (i.e., $\theta^+ = 0.5 > \theta^- = 0.1$). This choice is consistent with the U.S. regulatory environment. On the financing side, the annual risk free rate is calibrated as 0.015 as in Nikolov, Schmid and Steri (2013). The linear cost of equity issuance, λ_1, is 0.1, an intermediate value with respect to the estimates and calibration choices in the literature which range from 0.06 (Gomes, 2001) to 0.30 (Cooley and Quadrini, 2001). The fixed cost of equity issuance, λ_0, is equal to 0.05 which is close to the value used in Riddick and Whited (2009).

I now focus on the main set of parameters: the separation rate and the mobility rate parameters. The separation rate due to retirement, death, and disability is set to 0.05 according to JOLTS estimates. The mobility rate parameters are the ones for which there is no guidance in the literature. I choose the parameter on the aggregate shock, β_x, to be equal to 0.1 and the parameter on the idiosyncratic shock, β_z, to be equal to 0.05. With this choice the standard deviation of the mobility rate is equal to 0.10 which is definitely close to the standard deviation of the separation rate estimated in Quadrini and Sun (2013), 0.09. The mobility parameters are subject to a comparative statics exercise in the following section.

To compute the moments in the model, I simulate a large panel consisting of 2,000 firms and 300 periods, of which the first 200 are discarded as burn-in. The final simulated sample hence has a time span of 100 periods. The simulated moments are compared to the same moments in the data. Moments in the data are computed after removing firm and time fixed effects from the data to make volatilities of simulated and actual moments comparable (Nikolov, Schmid and Steri, 2013). Results of the calibration are reported in Table 7.

[Insert Table 7 about here]

1.4.2 Empirical Implications

In my model, a firm hold cash due to the fact that external financing is costly. I first quantify the effects of labor mobility on cash holdings by regressing the cash holdings on the mobility rate in my simulated panel. First, I regress cash holdings on

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the total mobility rate and then on the two components of the mobility rate (within and between mobility). Results are reported in Table 8 Panel A. One standard deviation increase in the mobility rate leads to an increase of roughly 10% on cash holdings, two-third of which can be attributed to the within-industry mobility and the remaining third to the between-industry mobility. I then focus on understanding when firms use cash and/or save cash. To this end, I consider the whole panel and two subsamples. In particular, I split my simulated panel into labor intensive and capital intensive firms[9]. In each period, I divide the cross-section of firms into deciles with respect to labor. I then define labor intensive the firms in the top three deciles of the distribution and capital intensive the firms in the bottom three deciles of the distribution. I then regress the change in cash on the change in both states, with robust standard errors, for the whole sample and for the two subsamples. Results are in Table 8 Panel B. The average firm (i.e., the whole sample) does upstate hedging, meaning that it accumulates cash to consume it when there is a positive change in productivity, given the positive coefficient in the regression. The interpretation is that firms save cash to be able to afford costly hiring adjustment costs and to sustain future wage bills when they are by a positive increase in productivity, given the persistence of the latter. However, from the sample split, we can appreciate that this results is driven by capital intensive firms. For labor intensive firms instead downstate hedging takes place, in the sense that large firms consume cash when they incur in a reduction of productivity. The intuition behind this result is that for labor intensive firms the wage bill represents a more serious burden, given its rigidity, and firms would like to hedge exactly when the are hit by a negative shock. In this case indeed the production is lower than expected but, nevertheless, the wage bill has to be paid (at least for one period). So, to avoid costly external financing when the productivity is low, labor intensive firms accumulate cash.

[Insert Table 8 about here]

Having assessed the reasons for which firms accumulate cash in my model, I analyze whether liquidity management decisions depends on the mobility rate. To obtain a set of empirical implications on the link between cash holdings, cash flow volatility and labor mobility, I compare different scenarios. I start from the baseline calibration. First, I consider the cases with low mobility, namely 75% of the baseline case parameters. Then, I take into account the high mobility cases, 150% of the baseline case parameters. I execute this exercise separately for the loadings of the

[9]In my model, the only production input is labor, so I can think as the capital to be normalized to one. This means that, in my model, labor intensive firms correspond to large firms and capital intensive firms correspond to small firms

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within-industry mobility and between industry mobility. Furthermore, when I change one parameter all the remaining ones are fixed to the baseline values. Table 8 Panels C and D reports the results of the comparative statics analysis.

The key analysis in my framework is to understand how the labor mobility affects the cash holdings and the cash flow volatility. Table 8 Panels C and D shows that as the parameters of the mobility rate increase, both the cash holdings and the cash flow volatility increase. These results are true both for the within industry mobility and the between industry mobility, even though they are stronger for the former case. Given the importance of these central predictions in my analysis, I state them explicitly as hypotheses.

H1: Cash Flow Volatility Hypothesis. Cash flow volatility is increasing in the mobility rate parameters.

H2: Cash Holdings Hypothesis. Cash holdings are increasing in the mobility rate parameters.

The economic intuition for the two results underlying these hypotheses is as follows. The mobility rate enters into the law of motion of labor. In my model, the firm has two reasons to accumulate cash: upstate hedging (i.e., firms accumulate cash to be able to hire if needed) and downstate hedging (i.e., firms accumulate cash to pay wage bills during downturns). Given the persistence of the productivity shocks, the hiring and firing decisions go quite often in the same direction of the flows induced by labor mobility. To be more precise, under the baseline calibration, the correlation between hiring rate and mobility rate amounts at 73.12%. However, the fact that these two rates are not perfectly correlated, represents a friction at the hiring level for the firm. Indeed, firms face the the economic trade-off between the costs of adjusting the labor force, and the profits from choosing a labor input that better responds to market conditions. As the mobility rate increases, when the hiring rate has the opposed sign, the effects of the aforementioned trade-off are more severe. Otherwise stated, for firms, it becomes more costly to chase the potential flows induced by labor mobility. As a result, given the rigidity of wage bills, cash flow volatility increases and firms hold more cash to hedge.

1.4.3 Data

My sample of firms is based on Compustat Industrial Annual files. The period for my main analysis is 1988-2011. Here I distinguish from the seminal paper on cash holding of Bates, Kahle and Stulz (2009) which starts in 1980, the reason being that data on

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labor mobility are available just starting from 1988. I remove firms from regulated industries (SIC 4900-4999) and financial firms (SIC 6000-6999). I remove observations with missing SIC code, total assets, cash and short term investments, sales, and operating income. The final sample consists in 84,820 firm-year observations, in which industries are defined by their 3-digit SIC code. Data on unionization rate are from the Union Membership and Coverage Database maintained by Barry Hirsch and David Macpherson. The definition of the variables is in Table 2, while summary statistics are in Table 9.

[Insert Tables 2 and 9 about here]

I then focus on discussing the major empirical challenge of this analysis: measuring labor mobility, that is the extent to which the workers are able or willing to move between different jobs, occupations, and geographical areas. The empirical works from labor economics used different sources/databases to measure labor mobility. For example, Topel and Ward (1992) rely on the Longitudinal Employee-Employer Data (LEED) to study the mobility patterns of young men. Oreopoulos, Von Wachter and Heisz (2006) employ three large administrative data sets collected and compiled within Statistics Canada to analyze the career development of college graduates. Kambourov and Manovskii (2009) use the Panel Study of Income Dynamics (PSID) to link occupational mobility and wage inequality. Despite the fact that all the cited databases allow to construct direct measures of labor mobility (i.e., tracking the career path of each worker), they suffer from the impossibility of being linked to standard accounting values in an extensive way (i.e., Compustat). So, I borrow a proxy of labor mobility from Donangelo (2014). This proxy is constructed using the Occupational Employment Statistics (OES) program from the Bureau of Labor Statistics (BLS) from 1988 to 2011. The database contains the information on occupations and industries. The rationale behind the proxy is that the degree of specificity of labor skills is mainly captured by occupation and is a key driver of workers' flexibility to switch jobs (e.g. Becker, 1964). The advantage of this proxy is that it captures the likelihood of the workers to switch job, hence it is an ex-ante measure of mobility. This features fits very well with my definition of mobility, which requires an unanticipated component. A caveat of this proxy is that it just captures the between-industry mobility and hence limits the tests of my model in the data. The methodology to construct the proxy is described in Appendix B.

Tesi di dottorato "Essays in Empirical Finance"
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1.4.4 Empirical Results

In this section, I test the key predictions from the theoretical analysis. First, I analyze the reasons to hold cash by comparing the results in the simulated sample to the results in the data. Second, I test the relation between cash flow volatility, cash holdings and labor mobility, by means of the proxy. Finally, I complement my empirical analysis with some robustness tests to better explore the precautionary savings motives in face of labor mobility and labor adjustments costs. In particular, I focus on financially constrained and unconstrained firms and I analyze the role of unions, which is closely related to labor mobility.

The Reasons to Hold Cash: Upstate and Downstate Hedging

In my model, given that external financing is costly, there are two reasons to hold cash: upstate hedging and downstate hedging, with the former effect prevailing for the average firm. To test whether these two effects are in place also in the data, I start by regressing the change in cash on the change in profitability. In the data, the cash to asset ratio is increasing over time (Falato, Kadyrzhanova and Sim, 2013), while in my model it has mean zero. So, to make them comparable, I first remove the trend from the data by means of Hodrick-Prescott filter and then I compute the growth rate. Profitability in the data is proxied by the total factor productivity (TFP) at firm level. TFP is the residual from estimating a log linear Cobb-Douglas production function for each firm and year. The estimates are provided by Imrohoroglu and Tuzel (2014). In the data, to define labor intensive and capital intensive firms, I compute the ratio of the number of employees on total assets (Serfling, 2013) and then I divide each year the distribution of firms into deciles. The firms in the top three deciles of the distribution are defined as labor intensive while the firm in the bottom three deciles are defined as capital intensive. I report a baseline specification without controls, to be directly comparable to the model, and a second specification with controls borrowed from Almeida, Campello and Weisbach (2004) when analyzing the cash flow sensitivity of cash. Results are reported in Table 10. Results are consistent with the two forces highlighted in the model, both for the whole sample and for the subsamples (labor intensive and capital intensive firms), separately.

[Insert Table 10 about here]

Labor Mobility and Cash Flow Volatility

I now focus on the relation between cash flow volatility and labor mobility, which has been shown to be positive through the comparative statics exercise (H1). To

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compute the firm-level volatility I follow Comin and Philippon (2006). First, I compute the growth rate of cash flow as

$$\gamma_{i,t} = \frac{cf_{i,t} - cf_{i,t-1}}{(|cf_{i,t}| + |cf_{i,t-1}|)/2}$$

where $cf_{i,t}$ is the cash flow of firm i in year t. Then, the firm-level volatility of cash flow is defined as the ten-years rolling standard deviation of the growth rate

$$\sigma_{i,t}(cf) = \frac{1}{10}\left[\sum_{\tau=0}^{9}(\gamma_{i,t-\tau} - \overline{\gamma}_{i,t})^2\right]^{\frac{1}{2}}$$

where $\overline{\gamma}_{i,t} = \frac{1}{10}\sum_{\tau=0}^{9}\gamma_{i,t-\tau}$ is the average growth rate over the previous ten-years. I then estimate the following model:

$$\sigma_{i,t}(cf) = \beta_1 mobility_{j,t} + \gamma X_{i,t} + \theta_t + \mu_i + \varepsilon_{i,t}$$

The subscripts i, j and t represent firm, industry and year, respectively. $\sigma_{i,t}(cf)$ is the firm-level volatility of cash flow. $mobility_{j,t}$ is the labor mobility measure for industry j, in year t, where firm i operates. My main focus is on the estimate of the coefficient β_1, which allows me to establish a relation between cash holdings and inter-industry labor mobility. $X_{i,t}$ is a set of determinants of cash flow volatility in a framework related to labor (Zhang, 2014). θ_t accounts for year fixed effects and μ_i accounts for time-invariant industry fixed effects. The definition of the variables is in Table 2, while summary statistics are in Table 9. I consider four different specifications: pooled OLS with robust standard errors, OLS with industry and year fixed effects and clustered standard errors by industry and year, Fama-MacBeth regression with Newey-West (1987) standard errors and pooled OLS regression with industry mean values and robust standard errors. Results are reported in Table 11.

Across specifications, the coefficient of labor mobility is positive and statistically significant. These results are consistent with the hypothesis that cash flow volatility is increasing with labor mobility. Firms facing more mobile workers exhibit higher cash flow volatility. When the mobility increases, the flows induced by mobility and the optimal hiring decisions of firms mismatch more often due to the presence of labor adjustments costs. As a result, firm's cahs flow are more volatile.

[Insert Table 11 about here]

Labor Mobility and Cash Holdings

In my model, the presence of labor mobility coupled with labor costs induces

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the firm to accumulate cash for precautionary savings motive (H2). To investigate whether cash holdings are used to hedge labor costs, I regress cash holdings on my proxy of labor mobility, while controlling for a set of standard determinants of cash holdings (Opler, Pinkowitz, Stulz and Williamson, 1999 and Bates, Kahle and Stulz, 2009). I estimate the following model:

$$cash_{i,t} = \beta_1 mobility_{j,t} + \gamma X_{i,t} + \theta_t + \mu_i + \varepsilon_{i,t}$$

The subscripts i, j and t represent firm, industry and year, respectively. $cash_{i,t}$ is the sum of cash and cash equivalents deflated by total asset. $mobility_{j,t}$ is the labor mobility measure for industry j, in year t, where firm i operates. My main focus is on the estimate of the coefficient β_1, which allows me to establish a relation between cash holdings and labor mobility. $X_{i,t}$ is a set of standard determinants of cash holdings. θ_t accounts for year fixed effects and μ_i accounts for time-invariant industry fixed effects. The definition of the variables is in Table 2, while summary statistics are in Table 9. I consider four different specifications: pooled OLS with robust standard errors, OLS with industry and year fixed effects and clustered standard errors by industry and year, Fama-MacBeth regression with Newey-West (1987) standard errors, pooled OLS regression with industry mean values and robust standard errors. Results are reported in Table 12.

[Insert Table 12 about here]

Across specifications, the coefficient of labor mobility is positive and statistically significant. It is also economic significant: a one standard deviation change in the measure of labor mobility leads to a change of cash holdings up to 2 %. This amount to about 10% of the sample mean value of cash holdings. Furthermore, control variables display the same sign as prior studies (Opler, Pinkowitz, Stulz and Williamson, 1999 and Bates, Kahle and Stulz, 2009). In particular, cash holdings are positively correlated with cash flow volatility (i.e., industry sigma). The inclusion of the cash flow volatility as control is crucial to assess the relevance of labor mobility. The latter represents a source of uncertainty for firms which is not entirely captured by cash flow volatility.

Among the covariates, I included the tangibility to control for the role of different asset structures (i.e., capital intensive and labor intensive). Along the same line of robustness, I run the same set of regressions splitting the sample between labor intensive and capital intensive firms. Indeed, in my model, physical capital is not explicitly included (i.e., it is normalized to one). Results are reported in Table 13. In

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this way I address the concern that the overall sample may reflect spurious differences in average cash holdings between capital intensive and labor intensive firms.

The dependent variable I use in the main analysis is likely to generate outliers. As robustness, I take the logarithm of cash holdings and I estimate the same set of specifications. Estimates reported in Table 14 confirm the prior results.

[Insert Tables 13-14 about here]

Financially constrained firms

In order to further investigate the precautionary motive to hold cash I focus on unconstrained and constrained firms. The latter have a higher benefit of holding cash and should increase their cash holdings more than financially unconstrained firms in response to increasing mobility. To test this prediction I need to identify constrained and unconstrained firms in the data. Since financial constraints are not observable at firm level, I rely on three different proxies used in the literature.

The first measure of financial constraints I use is firm size (e.g., Gilchrist and Himmelberg, 1995, and Erickson and Whited, 2000). Firm size is computed as the logarithm of net sales. Every year I divide firms into deciles with respect to size. I define financially constrained firms these in bottom three deciles of the distribution of size and financially unconstrained firms these in top three deciles of the distribution of size.

The second measure of financial constraint I consider is the payout ratio (e.g., Fazzari, Hubbard and Petersen, 1987). Payout ratio is computed as the ratio of total distributions (dividends and stock repurchases) to operating income. As for the previous criterion, I divide firms into deciles with respect to payout ratio. I define financially constrained firms these in bottom three deciles of the distribution of payout ratio and financially unconstrained firms these in top three deciles of the distribution of payout ratio.

Finally, I use the Whited and Wu financial constraints index. The index is computed as follows:

$$\begin{aligned} WW &= -0.091 * CF - 0.062 * DivDummy + 0.021 * TLTD \\ &\quad -0.044 * LNTA + 0.102 * ISG - 0.035 * SG \end{aligned}$$

where CF is operating cash flow, $DivDummy$ is a dummy variable which takes value one if the firm pays dividends, $TLTD$ is the ratio of long term debt over total assets, $LNTA$ is the logarithm of total assets, ISG is the three-digit SIC industry

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sales growth rate and SG is the firm sales growth rate. I compute the Whited and Wu index every year. Then, I define financially constrained firms these in top three deciles of the distribution of Whited and Wu index and financially unconstrained firms these in bottom three deciles of the distribution of Whited and Wu index.

As pointed out in Morellec, Nikolov and Zucchi (2013), these three criteria are correlated but not perfectly overlapping. They provide incremental information and contribute to the robustness of the analysis.

To test whether financially constrained firms hold more cash than financially unconstrained firms when facing labor mobility, I repeat the main analysis by splitting the sample into two subsamples (i.e., financially constrained and unconstrained firms) and testing that the coefficient on mobility for financially constrained firms is not lower than the same coefficient for financially unconstrained firms (Table 15 Panel A). Result are qualitatively comparable when I include an indicator variable which is equal to one if the firm is financially constrained, an interaction term and I restrict the sample just to financially constrained and unconstrained firms.

Unions

So far, I provided evidence that cash holdings and labor mobility are positively correlated. In the literature, it has been shown that labor mobility is related to another feature of workforce: unions. In the remainder of this section, I analyze the interaction of this characteristic and labor mobility.

Unionized workers tend be less mobile (Chen, Kacperczyk and Ortiz-Molina, 2011). However the effect of unionization on liquidity management of firms is ambiguous. Klasa, Maxwell and Ortiz-Molina (2009) show that firms facing a more unionized workforce tend to hold less cash while Schmalz (2013) find the opposite but just for unconstrained firms. The former result is consistent with a collective bargaining theory (i.e., firms hold less cash to be less vulnerable to the threats of powerful unions). The latter result assimilates labor force to physical assets, the effect of the unions is then to increase liquidation costs. For robustness, I hence add as control to my main specifications the unionization rate. Data on unionization rate are from the Union Membership and Coverage Database maintained by Barry Hirsch and David Macpherson. The database adopts the 3-digit Census Industry Classification (CIC) code. This code has to be converted into the SIC. This conversion is possible just for the manufacturing sector with CIC codes between 100 and 392. This data availability restricts the sample for which I have both the mobility proxy and the unionization rate to 28,312 firm-year observations. The unionization rate is negatively correlated with cash holdings, consistently with the collective bargaining hypothesis.

Tesi di dottorato "Essays in Empirical Finance"
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The inclusion of this additional control does not affect the significance both statistical and economical, of labor mobility proxy. This result confirms that labor mobility captures a novel channel which is just partially related to existing explanations in the interaction of liquidity management and labor. Results are reported in Table 15 Panel B.

[Insert Table 15 about here]

1.5 Conclusions

This paper examines whether firms hedge their labor costs with cash. To this end, I first provide new evidence that cash holdings shrink when the mobility of employees is reduced. In particular, I exploit as a negative shock to labor mobility, the exogenous and unexpected enforcement of agreements not to compete in Michigan in 1985 by means of the Michigan Antitrust Reform Act. To rationalize this finding and to produce a set of testable predictions, I built an industry equilibrium model where firms make hiring and firing decisions, as well as liquidity management decisions, in the presence of a mobile workforce. In the model, workforce mobility generates from the comparison of the expected future performance of the firm and other firms, both in the same industry (within-industry mobility) and in other industries (between-industry mobility). Liquidity management decisions are related to the use of cash, whose value stems from costly external financing. Firms hedge wage bills and hiring and firing costs with cash. Labor intensive firms do more downstate hedging, meaning that they hold cash to cover wage bills in bad times. While capital intensive firms do more upstate hedging, saving cash to be able, in good times, to seize growth opportunities and related hiring costs. I find the same patterns in the data.

I then show, both in my model and the data, that cash flow volatility increases with labor mobility and firms hold more cash to hedge this riskiness. The effect of labor mobility on cash holdings are stronger for financially constrained firms, in a way consistent with a precautionary savings motive. Furthermore, results are robust to standard determinants of cash holdings.

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
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Appendix A: Computation Algorithm

I start by characterizing the state and choice variables of the model. They are discretized over a grid. In particular, I specify a grid with 25 points for labor, 15 for cash and 15 for net worth with upper bounds $\bar{n}$, $\bar{c}$ and $\bar{w}$, respectively. In my model cash is between zero and 1 as if it is normalized by total assets, so to be comparable with the cash to asset ratio in the data. The upper bound are large enough to be nonbinding at all times. The grids are constructed recursively, following McGrattan (1999) which is, for a generic variable u, $u_i = u_{i-1} + c_1 exp(c_2(i-2))$, where $i = 1, 2, ..., N$ and N are the points of the grid and c_1 and c_2 are two constant chosen to provide a desirable upper bound $\bar{u}$. The method will generate more grid points around the lower bound where the value function has most of its curvature.

The state variable x and z are defined on continuous state spaces, which have to be transformed into discrete state space. This goal is achieved using the method of Tauchen and Hussey (1991), which performs well given that in my case the persistence of the processes are below the threshold of 0.9. I use 7 points for the idiosyncratic shock and 2 points for the aggregate shock (i.e., good and bad state). Also the state space of the log output p has been discretized on an even-spaced grid of three points. The lower and the upper bound for p are chosen so that the simulated path of the log output price never hits the bounds.

The solution of the model entails a primary obstacle: the endogeneity of the log output price, which depends on the cross-sectional distribution of the firms (Zhang, 2005). In particular, output depends on all moments of the current distribution of firms. To deal with this high-dimensional problem, I follow the "approximate aggregation" idea of Krusell and Smith (1998). The idea is to approximate the distribution μ_t with a finite set L of moments m_L in addition to x_t. Firms perceive the law of motion for m_L as a function Γ_L, which expresses the L moments in the next period as a function of the same moments in the current period. In formulas, $m_{Lt+1} = \Gamma_L(m_{Lt}, x_{t,t+1})$. Given this law of motion, the policy rule for a single firm can be derived. Once, I solve the individual problem of the firm, given an initial labor stock and net worth, it is possible to derive the implied time-series path of the firms distribution by simulating the behavior of a large panel of firms. The resulting distribution is then used to compare the simulated evolution of the vector of moments m_L to the perceived law of motion for m_L, on which the behavior of the firms is based. The approximate equilibrium is a function Γ_L^* which, when taken as given by firms, provides a fit which is very good. So, even though firms do not take into account all the moment of the distribution, the forecasting errors resulting from this omission are negligible.

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
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In my case, I choose L equal to one and m_L is equal to the log output price p. I then assume that the log output price follows a linear functional form:

$$p_{t+1} = \delta_1 + \delta_2 p_t + e_{t+1} \tag{12}$$

The algorithm amounts to the following iterative procedure: (1) guess the parameter of the functional form (12) ($\delta_1 = 0$ and $\delta_2 = 1$ for all the aggregate states); (2) Solve the firm's individual problem, via value function iteration; (3) Simulate a panel of N firms for T periods using the policy rules; (4) estimate the functional form (12) and obtain measures of goodness-of-fit; (5) if the estimation gives parameter values which are very close to those in the last iteration and the goodness-of-fit is satisfactory, stop. The goodness-of-fit measures I consider are the R^2 and the standard deviation of the error of the estimation of the equation (12).

For the inner loop, the individual problem of the firm, the convergence criterion is $err_V < 1e-4$ where $err_V = |V_i - V_{i-1}|$ and V_i is the value function at iteration i. For the outer loop, the computation of the approximating equilibrium, the convergence criterion is $err_\delta < 1e-4$ where $err_\delta = |\delta_j - \delta_{j-1}|$ and δ_j is the vector of coefficients of 12 at iteration j.

I simulate 2,000 firms for 300 periods. Then I drop the first 200 observations of each time series to make sure that firms are in their steady state.

With benchmark parametrization, I obtain the following approximate equilibrium: (1) good state, $\delta_1 = 0.1150$, $\delta_2 = 0.9014$,$R^2 = 0.7803$ and $\sigma_e = 0.0049$; (1) bad state, $\delta_1 = 0.1291$, $\delta_2 = 0.8903$,$R^2 = 0.8155$ and $\sigma_e = 0.0047$. I conclude that the quality of the aggregation is overall good.

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
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Appendix B: Mobility Measure

Following Donangelo (2014), labor mobility measure is constructed using data form the Occupational Employment Statistics (OES) program from the Bureau of Labor Statistics (BLS) from 1988 to 2011. Workers in mobile occupation can be employed across a larger number of industries than workers in immobile occupations. Given this intuition, the measure is constructed in two steps. First, for each occupation, I compute the ratio of the number of industries in which that occupation is found to the total number of industries. (Hereafter, I refer this ratio to as the "concentration score"). The higher the ratio, the lower the human capital specificity of the occupation and the higher the opportunities to switch industry. At this stage all the occupations which require little or no preparation are aggregated in a fictitious occupation. In particular, all the occupation classified in job zone 1 from the O*Net index are aggregated. Second, for each industry, I weight the concentration score of each occupation to give me an industry-level mobility measure. A higher value of the mobility measure implies that workers in the industry have more flexibility to switch industry in response to better opportunities. In sum, my industry-level measure of labor mobility is given by:

$$mobility_{i,t} = \left(\sum_j Oconc_{j,t} \times \frac{emp_{i,j,t} \times wage_{i,j,t}}{\sum_j emp_{i,j,t} \times wage_{i,j,t}} \right)$$

where $mobility_{i,t}$ is a measure of labor mobility for industry i, j indexes occupations. $emp_{i,j,t}$ is the number of workers assigned to occupation j who are employed in industry i at year t. $wage_{i,j,t}$ is the mass of wages paid to workers in industry i who are assigned to occupation j at year t. $Oconc_{j,t}$ is the concentration score of occupation j. This proxy is meant to capture the decisions of workers to switch job in response to better opportunities. Stated differently, when the performance of the industry are relatively good, we should expect an inbound of workers and when the performance of the industry are relatively bad we should expect an outbound of workers.

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Table 2: **Variables Definition**
Table 2 includes the definition of the variables used the empirical analyses.

Variable	Variable Definition
Dependent Variable	
Cash	Cash and Short-Term Investments (CHE)/ Assets - Total (AT)
Cah flow volatility	See Section 1.4.4
Mobility	See Section 1.5
Intensity of Financial Constraint	
Payout	(Dividends - Common (DVC) + Purchase of Com. & Pref. Stock (PRSTKC)) / Operating Income Before Deprec. (OIBDP)
Size	log(Sales net (SALE))
Whited-Wu index	See Section 1.4.4
Control Variables	
Book Debt	Long term debt (DLTT) + Debt in current liabilities (DLC)
Book Equity Assets	(Market value (CSHO * PRCC) + Book debt)/Assets - Total (AT)
Market-to-Book	(Market value (CSHO * PRCC) + Book debt)/Assets - Total (AT)
Market Cap	Market value (CSHO * PRCC) (in 1990 dollars)
Firm Size	Assets - Total (AT) (in 1990 dollars)
Cash Flow	(EBITDA - Interest - Taxes - Common Dividend)/Assets- Total (AT)
Net Working Capital (NWC)	(Working Capital (WCAP) - Cash and Short-Term Investments (CHE)/ Assets - Total (AT)
Capex	Capital Expenditures (CAPX)/Assets - Total (AT)
Book Leverage	Book Debt/(Assets Total (AT) - Book equity + Market value (CSHO * PRCC))
Industry Sigma	See Section 1.4.4
Dividends Dummy	Dummy variable equal to 1 if Dividends - Common (DVC) reported
R&D	Research and development expenses (XRD)/Assets total (AT)
Aquisitions	Acquisitions (AQC)/Assets - Total (AT)
Tangibility	Property, Plant and Equipment - Net (PPENT)/Assets - Total (AT)
Employees (Emp)	Number of employees (EMP)/Assets - Total (AT)
TFP	See Section 1.4.4
IPO1 through IPO3	Dummy variable equal to 1 if the firm went public 1, 2, 3 years ago

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
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Table 3: **MARA: Descriptive Statistics and Univariate Difference-in-Differences Analysis**

Table 3 Panel A reports descriptive statistics for the main variable used in the estimation. The sample is based on Compustat Annual Industrial files over the period 1976 - 1995 for the firms located in Alaska, California, Connecticut, Michigan, Minnesota, Montana, North Dakota, Nevada, Oklahoma, Washington, and West Virginia. Firms from regulated industries (SIC 4900-4999) and financial industries (SIC 6000-6999) are excluded. All continuos variables are winsorized at 1% and 99%. Book leverage is winsorized above at 1. Table 2 provides a detailed definition of the variables. Table 3 Panel B reports the average difference in cash/assets, both before and after MARA, and between Michigan and comparison states. The descriptive "difference-in-differences" (DiD) effect appears in the lower-right cell and is equal to the difference of the other two differences. The DiD effect of -0.055 corresponds to the coefficient estimate of -0.055 reported in Table 4 Column 1 (the basic DiD model with no year fixed effects, industry fixed effects).

Panel A: Descriptive Statistics									
	Mean	Std Dev	Min	p5	p10	p50	p90	p95	Max
Cash	0.168	0.201	0.000	0.004	0.009	0.084	0.477	0.629	0.940
Market-to-Book	2.060	2.023	0.413	0.768	0.858	1.372	3.893	5.646	1.877
Firm Size	6.158	2.547	0.000	0.010	0.028	0.490	9.331	23.974	325.138
Cash Flow	-0.002	0.239	-1.881	-0.444	-0.217	0.060	0.151	0.188	0.356
NWC/asset	0.134	0.228	-1.127	-0.216	-0.106	0.146	0.403	0.474	0.654
Capex	0.082	0.089	0.000	0.005	0.012	0.055	0.181	0.255	0.664
Book Leverage	0.452	0.241	0.011	0.101	0.153	0.430	0.788	1.000	1.000
R&D	0.213	1.381	0.000	0.000	0.000	0.003	0.164	0.395	5.200
Dividends Dummy	0.351	0.477	0.000	0.000	0.000	0.000	1.000	1.000	1.000
Acquisitiona	0.012	0.046	0.000	0.000	0.000	0.000	0.025	0.077	0.551
Industry Sigma	0.054	0.028	0.002	0.019	0.022	0.047	0.096	0.109	0.252
Tangibility	0.295	0.215	0.000	0.038	0.062	0.245	0.633	0.750	0.944
Michigan	0.113	0.317	0.000	0.000	0.000	0.000	1.000	1.000	1.000
After	0.611	0.487	0.000	0.000	0.000	1.000	1.000	1.000	1.000

Panel B: Univariate Difference-in-Differences Analysis			
Cash/Asset	Before	After	Difference
Michigan	0.114	0.134	0.020
Control Group	0.128	0.203	0.075
Difference	0.014	0.069	-0.055

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Table 4: **MARA and Cash Holdings**
Table 4 reports the coefficient estimates of the effect of MARA on cash holdings. Column 1 reports the results for the OLS regression. Column 2 reports the result for the OLS regression with additional controls. Column 3 reports the results for the OLS regression with additional controls, firm and year fixed effects. Variable definitions are provided in the Table 2. Standard errors clustered by firm are reported under the coefficients in parenthesis. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)
	OLS	OLS	FE
Dependent variable	Cash	Cash	Cash
Michigan	-0.014	0.014**	0.017**
	(0.010)	(0.007)	(0.008)
After	0.074***	-0.007*	-0.009
	(0.005)	(0.004)	(0.007)
Michigan*After	-0.055***	-0.020**	-0.020**
	(0.013)	(0.009)	(0.009)
Market-to-Book		0.008***	0.007***
		(0.001)	(0.001)
Firm Size		0.004***	0.004**
		(0.001)	(0.002)
Cash Flow		0.010	0.012
		(0.010)	(0.010)
NWC		-0.444***	-0.432***
		(0.015)	(0.015)
Capex		0.041**	0.034*
		(0.020)	(0.018)
Book Leverage		-0.485***	-0.480***
		(0.013)	(0.012)
R&D		0.019***	0.016***
		(0.002)	(0.002)
Dividend Dummy		-0.020***	-0.015***
		(0.005)	(0.005)
Acquisitions		-0.264***	-0.230***
		(0.026)	(0.025)
Industry Sigma		0.296***	0.318***
		(0.077)	(0.090)
Tangibility		-0.423***	-0.438***
		(0.014)	(0.016)
Constant	0.128***	0.546***	
	(0.004)	(0.013)	
Industry FE	N	N	Y
Year FE	N	N	Y
Observations	14,571	14,571	14,571
R^2	0.035	0.606	0.641

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Table 5: **MARA and Cash Holdings: Robustness Tests**
Table 5 reports the coefficient estimates of the robustness tests on the effect of MARA on cash holdings starting from the baseline specification (Table 4, Column 3). Column 1 adds to baseline specification the additional controls for automotive industry (i.e., $Michigan * Auto$, $After * Auto$ and $Michigan * After * Auto$). Column 2 and 3 reports the sample split for R&D and not R&d firms, respectively. For these two specifications the variable R&D/sale is omitted. Column 4 reports the results over a shorter window (-/+5 years). Column 5 reports the results when the control group is represented by all U.S. states. Column 6 reports the results using as dependent variable the logarithm of the cash to assets ratio. Variable definitions are provided in the Table 2. Standard errors clustered by firm are reported under the coefficients in parenthesis. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
	Automotive	R&D	NO R&D	Short Window	All States	
Dependent variable	Cash	Cash	Cash	Cash	Cash	log(Cash)
Michigan	0.019**	0.009	0.022***	0.018**	0.013***	0.289***
	(0.008)	(0.009)	(0.004)	(0.008)	(0.003)	(0.080)
After	-0.009	-0.016	-0.016**	-0.003	-0.022***	-0.469***
	(0.007)	(0.013)	(0.007)	(0.007)	(0.002)	(0.071)
Michigan*After	-0.026***	-0.040***	-0.013**	-0.016*	-0.011**	-0.263***
	(0.010)	(0.012)	(0.005)	(0.009)	(0.005)	(0.090)
Market-to-Book	0.007***	0.005***	0.005***	0.006***	0.006***	0.054***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.010)
Firm Size	0.004**	0.005***	-0.002**	0.004**	-0.001***	0.061***
	(0.002)	(0.001)	(0.001)	(0.002)	(0.000)	(0.013)
Cash Flow	0.012	-0.015	0.030**	0.011	0.014***	0.084
	(0.010)	(0.010)	(0.012)	(0.010)	(0.004)	(0.075)
NWC	-0.432***	-0.569***	-0.313***	-0.420***	-0.376***	-2.772***
	(0.015)	(0.016)	(0.011)	(0.016)	(0.004)	(0.113)
Capex	0.033*	0.072**	0.051***	0.043**	0.036***	0.738***
	(0.018)	(0.035)	(0.015)	(0.019)	(0.006)	(0.198)
Book Leverage	-0.480***	-0.638***	-0.332***	-0.478***	-0.415***	-3.389***
	(0.012)	(0.012)	(0.009)	(0.013)	(0.003)	(0.097)
R&D	0.016***			0.018***	0.018***	0.023***
	(0.002)			(0.002)	(0.001)	(0.006)
Dividend Dummy	-0.015***	-0.038***	0.009***	-0.015***	-0.014***	0.009
	(0.005)	(0.005)	(0.003)	(0.005)	(0.001)	(0.043)
Acquisitions	-0.230***	-0.334***	-0.160***	-0.215***	-0.175***	-1.305***
	(0.025)	(0.040)	(0.024)	(0.026)	(0.009)	(0.239)
Industry Sigma	0.325***	0.174	0.288***	0.242**	0.150***	2.481***
	(0.091)	(0.131)	(0.080)	(0.094)	(0.029)	(0.847)
Tangibility	-0.439***	-0.636***	-0.336***	-0.440***	-0.401***	-2.844***
	(0.016)	(0.020)	(0.011)	(0.017)	(0.004)	(0.146)
Michigan*Auto	-0.004					
	(0.027)					
Michigan*After*Auto	0.026					
	(0.030)					
After*Auto	0.008					
	(0.024)					
Industry FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
Observations	14,571	6,007	8,564	11,732	72,389	14,455
R^2	0.642	0.719	0.499	0.632	0.574	0.472

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Table 6: **MARA and Cash Holdings: Placebo Tests**
Table 6 reports the coefficient estimates of the placebo tests on Delaware (Column 2) and Texas (Column 3). Results are reported also for Michigan (Column 1) for easiness of comparison. The treatment year is 1986 for Michigan, 1981 for Delaware and 1983 for Texas. The window is symmetric and spans from -10 to +10 years with respect to the treatment year. The specification is the same used in Table 5 (Column 5). The dependent variable is the cash/assets. Variable definitions are provided in the Table 2. Standard errors clustered by firm are reported under the coefficients in parenthesis. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)
	Michigan	Delaware	Texas
Dependent variable	Cash	Cash	Cash
Treated State	0.013***	0.000	0.001
	(0.003)	(0.003)	(0.004)
After	-0.022***	-0.005	0.001
	(0.002)	(0.003)	(0.003)
Treated State*After	-0.011**	0.015***	-0.006
	(0.005)	(0.004)	(0.005)
Market-to-Book	0.006***	0.006***	0.005***
	(0.000)	(0.001)	(0.001)
Firm Size	-0.001***	-0.002***	-0.003***
	(0.000)	(0.001)	(0.001)
Cash Flow	0.014***	0.017***	0.045***
	(0.004)	(0.005)	(0.006)
NWC	-0.376***	-0.375***	-0.368***
	(0.004)	(0.007)	(0.007)
Capex	0.036***	0.040***	0.030***
	(0.006)	(0.009)	(0.009)
Book Leverage	-0.415***	-0.408***	-0.380***
	(0.003)	(0.006)	(0.006)
R&D	0.018***	0.019***	0.053***
	(0.001)	(0.001)	(0.004)
Dividend Dummy	-0.014***	-0.012***	-0.009***
	(0.001)	(0.002)	(0.002)
Acquisitions	-0.175***	-0.155***	-0.131***
	(0.009)	(0.011)	(0.011)
Industry Sigma	0.150***	0.123***	0.132***
	(0.029)	(0.041)	(0.045)
Tangibility	-0.401***	-0.398***	-0.383***
	(0.004)	(0.008)	(0.008)
Industry FE	Y	Y	Y
Year FE	Y	Y	Y
Observations	72,389	68,398	61,961
R^2	0.574	0.566	0.553

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Table 7: **Model Calibration**

Table 7 reports actual and simulated moments, together with the corresponding choice of structural parameters. Calculations of data moments are based on Compustat Annual Industrial files over the 1988-2011 period. Panel A reports the moments from a simulated panel of firms, and the corresponding moments from the data. Operating income is defined as $e^{x_t+z_{i,t}}n_{i,t}^{\alpha} - wg_{i,t}n_{i,t}$. Equity issues as $|min(e,0)|$. Cash holdings as c. Cash holdings growth as $(c_{t+1}-c_t)/c_t$. Employment growth as $(n_{t+1}-n_t)/n_t$. Cash flow as $\pi_t(n_t,z_t;x_t,p_t)+c_t(1+r(1-\tau))-c_{t+1}-a(h_t,n_t)$. Panel B reports the chosen values for structural parameters. η is the inverse of the price elasticity. α is the curvature of the profit function. θ^+ and θ^- are the convex adjustment costs parameters. $m(z_t;x_t) \equiv \beta_z[z_t - E(z_t)] + \beta_x[x_t - E(x_t)]$ is mobility rate and labor accumulates according to the law $n_{t+1} = h_t + (1-s-m(z_t;x_t))n_t$ where s is the (average) separation rate. β_z is the sensitivity to the deviation from the mean of the idiosyncratic shock z_t and β_x is the sensitivity to the deviation from the mean of the aggregate shock x_t. ρ_z and σ_z are the serial correlation and the standard deviation to the idiosyncratic shock z_t. μ_x,ρ_x,σ_x are the mean, the serial correlation and the standard deviation to the aggregate shock x_t. λ_0 and λ_1 fixed and proportional equity flotation costs. wg_1 and wg_2 are the parameters of the wage process $wg_t = wg_1 exp(wg_2(x_t+z_t))$. The remaining parameter are r, the interest rate, and τ, the tax rate. They are set to 0.015 and 0.35 to be approximately equal to the real interest rate in the 20th century and to the statutory tax rate in the United States.

Panel A: Moments		
	Simulated	Data
Mean of operating income	0.041	0.034
Variance of operating income	0.011	0.007
Serial correlation of operating income	0.650	0.570
Mean of equity issues	0.060	0.065
Variance of equity issues	0.004	0.003
Mean of cash holdings	0.201	0.196
Variance of cash holdings	0.005	0.0121
Serial correlation of cash holdings	0.686	0.359
Variance of cash holdings growth	0.010	0.026
Serial correlation of cash holdings growth	-0.018	-0.057
Variance of employment growth	0.065	0.048
Serial correlation of employment growth	0.033	0.018
Variance of cash flow	0.010	0.026
Correlation of operating income growth and employment growth	0.003	0.002
Correlation of cash holdings growth and employment growth	-0.007	-0.038

Panel B: Calibrated Parameters													
α	θ^+	θ^-	β_z	β_x	ρ_z	σ_z	μ_x	ρ_x	σ_x	λ_0	λ_1	wg_1	wg_2
0.650	0.500	0.100	0.050	0.100	0.725	0.500	-2.000	0.800	0.050	0.100	0.050	0.075	0.100

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Table 8: **Model: Cash and Mobility**
Table 8 reports the coefficients of regressions from simulated data in the model. Panel A reports the regression of cash holdings on the mobility rates, total ($\beta_z[E_t(z_{t+1}|z_t) - E(z_{t+1})] + \beta_x[E_t(x_{t+1}|x_t) - E(x_{t+1})]$) , within ($\beta_z[E_t(z_{t+1}|z_t) - E(z_{t+1})]$) and between ($\beta_x[E_t(x_{t+1}|x_t) - E(x_{t+1})]$), respectively. Panel B report the regressions of the change in cash holdings on the change in the aggregate and idiosyncratic productivity shocks, respectively. Regressions in Panel B are run for the full sample and for the two subsample of capital intensive and labor intensive firms, respectively. Capital intensive firms are the firms in the bottom three deciles of the distribution of n, while labor intensive firms are the firms in the top three deciles of the distribution of n. Robust standard errors are reported in parentheses. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Panel C and D report the results of the comparative statics exercise on the loadings of the mobility rate, both within and between. All the other parameters are left to the same values of the baseline calibration.

	Panel A		Panel B		
	(1)	(2)	(3)	(4)	(5)
Dependent variable	Full Sample Cash Holdings	Full Sample Cash Holdings	Full Sample △ Cash	Capital Intensive △ Cash	Labor Intensive △ Cash
Mobility Rate	0.468***				
	(0.021)				
Mobility Rate (within)		0.462***			
		(0.021)			
Mobility Rate (between)		4.876***			
		(0.053)			
△ Idiosyncratic Shock			-0.008***	-0.018***	0.001***
			(0.000)	(0.000)	(0.000)
△ Aggregate Shock			-0.287***	-1.202***	0.664***
			(0.026)	(0.031)	(0.041)
Constant	0.166***	0.165***	0.000***	0.009***	-0.009***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	200,000	200,000	198,000	59,400	59,400

Panel C: Comparative statics on β_z			
	Baseline	$0.75 * \beta_z$	$1.5 * \beta_z$
Mean of cash holdings	0.2016	0.1669	0.2449
Variance of cash flow	0.0101	0.0084	0.0142

Panel D: Comparative statics on β_x			
	Baseline	$0.75 * \beta_x$	$1.5 * \beta_x$
Mean of cash holdings	0.2016	0.1825	0.2224
Variance of cash flow	0.0101	0.0082	0.0129

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Table 9: **Descriptive statistics**
The following table reports the summary statistics for the variable used in the analysis according to the filters described in the text. The period is 1988-2011. All the variables have been winsorized to 1%. Book leverage as in Opler, Pinkowitz, Stulz and Williamson (1999) is winsorized so that the maximum is equal to one.

	Mean	Std Dev	Min	p5	p10	p50	p90	p95	Max	Obs
Cash	0.192	0.223	0.000	0.005	0.012	0.0811	0.614	0.865	0.962	84,820
Cash Flow Volatility	0.547	0.451	0.051	0.085	0.112	0.355	1.266	1.670	2.108	84,820
Market-to-Book	1.153	1.115	0.344	0.731	0.822	1.343	5.014	10.572	38.891	84,820
Firm Size (log of)	2.211	2.103	-4.924	-3.036	-2.397	0.153	3.966	5.487	7.014	84,820
Cash Flow	0.003	0.248	-2.627	-0.324	-0.132	0.063	0.184	0.262	0.393	84,820
NWC	0.284	2.105	-1.434	-0.203	-0.112	0.115	0.456	0.577	0.742	84,820
Capex	0.063	0.082	0.000	0.005	0.012	0.053	0.221	0.404	0.663	84,820
Book Leverage	0.452	0.235	0.011	0.112	0.153	0.424	0.935	1.000	1.000	84,820
R&D	0.433	3.502	0.000	0.000	0.000	0.000	0.673	10.181	120.382	84,820
Acquisitions	0.024	0.064	0.000	0.000	0.000	0.000	0.143	0.344	0.543	84,820
Mobility	1.153	1.113	0.112	0.217	0.283	0.373	3.165	3.516	6.069	84,820
Sales	0.071	2.409	-8.430	-3.908	-2.887	0.083	4.076	5.537	6.570	84,820
Tangibility	0.276	0.234	0.000	0.024	0.040	0.204	0.777	0.906	0.944	84,820
Emp	1.277	4.019	0.000	0.081	0.157	0.717	2.346	3.504	257.429	84,820
Industry Sigma	0.070	0.036	0.002	0.022	0.028	0.065	0.121	0.132	0.162	84,820
IPO1	0.078	0.268	0.000	0.000	0.000	0.000	0.000	1.000	1.000	84,820
IPO1	0.075	0.263	0.000	0.000	0.000	0.000	0.000	1.000	1.000	84,820
IPO1	0.069	0.254	0.000	0.000	0.000	0.000	0.000	1.000	1.000	84,820
Dividend Dummy	0.327	0.469	0.000	0.000	0.000	0.000	1.000	1.000	1.000	84,820
Market Cap	17.395	85.783	0.000	0.041	0.078	1.156	25.831	67.431	3539.031	84,820
TFP	-0.637	0.428	-1.966	-1.267	-1.064	-0.636	-0.177	0.024	2.727	84,820

Table 10: **Upstate and downstate hedging**
Table 10 reports the coefficients of the regressions of the growth of cash holdings on the change in total factor productivity (TFP). The growth of cash holdings is computed after removing the trend with Hodrick-Prescott filter. TFP is the residual from estimating a log linear Cobb-Douglas production function for each firm and year. The sample is based on Compustat Annual Industrial files over the 1988-2011 period and it consists of 39,892 firm-year observations. Panel A reports a pooled OLS regression with robust standard errors. Panel B reports a pooled OLS regression with controls and robust standard errors. Results are reported for the full sample (Column 1 and 4), and for the two subsamples of capital intensive and labor intensive firms (Columns 2, 5 and Columns 3, 6, respectively). Capital intensive firms are the firms in the bottom three deciles of the distribution of the number of employees over total assets, while labor intensive firms are the firms in the top three deciles of the distribution of the number of employees over total assets. Variable definitions are provided in the Table 2. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	Panel A			Panel B		
	(1)	(2)	(3)	(4)	(5)	(6)
	Full	Capital	Labor	Full	Capital	Labor
1988-2011	Sample	Intensive	Intensive	Sample	Intensive	Intensive
Dependent variable	△ Cash	△ Cash	△ Cash	△ Cash	△ Cash	△ Cash
△ TFP	-0.003***	-0.003***	0.250*	-0.003***	-0.003***	0.239*
	(0.000)	(0.000)	(0.129)	(0.000)	(0.000)	(0.129)
Market-to-Book				0.324	0.319*	0.618
				(0.232)	(0.183)	(0.662)
Firm Size				0.127	0.281	0.420
				(0.158)	(0.328)	(0.316)
Cash Flow				-6.958**	-3.166	-4.842
				(3.420)	(6.687)	(4.299)
NWC				3.846	-4.757	-5.432
				(6.878)	(8.064)	(4.741)
Capex				11.169***	17.398**	10.602
				(3.967)	(8.450)	(9.449)
Book Leverage				0.508	-8.800	2.247
				(3.124)	(7.170)	(4.532)
Constant	-0.663	-1.530**	-1.909*	-2.063	0.250	-3.455
	(0.918)	(0.733)	(1.083)	(1.522)	(2.097)	(4.180)
Observations	39,892	9,483	12,858	36,855	8,436	12,142
R^2	0.000	0.000	0.000	0.000	0.001	0.000

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Table 11: **The effect of labor mobility on cash flow volatility**
Table 11 reports the coefficients of the regressions of cash flow volatility ($\sigma(cf)$) on labor mobility and control variables. The dependent variable is ten-years rolling standard deviation of the growth rate of the ratio of cash and cash equivalents to assets. The sample is based on Compustat Annual Industrial files over the 1988-2011 period and it consists of 40,151 firm-year observations. Column 1 reports a pooled OLS regression with robust standard errors. Column 2 reports an OLS regression with year and industry fixed effects and standard errors clustered by year and industry. Column 3 reports a Fama-MacBeth regression with Newey and West (1987) standard errors to control for autocorrelation up to 5 lags. Column 4 reports a pooled OLS regression with mean values at 3-digit SIC industries and robust standard errors. Variable definitions are provided in the Table 2. For the fixed effects regression, I report within R^2. Standard errors are reported in parentheses. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)
1988-2011	OLS	FE	Fama-MacBeth	Industry
Dependent variable	$\sigma(cf)$	$\sigma(cf)$	$\sigma(cf)$	$\sigma(cf)$
Mobility	0.031***	0.027**	0.141*	0.005***
	(0.002)	(0.011)	(0.078)	(0.001)
Market-to-Book	-0.024***	-0.022***	-0.037***	0.005***
	(0.002)	(0.005)	(0.008)	(0.001)
Firm Size	-0.129***	-0.125***	-0.128***	0.000***
	(0.001)	(0.006)	(0.004)	(0.000)
Market Cap	0.000***	0.000**	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)
Emp	0.000***	0.000*	0.000***	-0.015***
	(0.000)	(0.000)	(0.000)	(0.001)
Constant	0.738***		0.667***	0.056***
	(0.004)		(0.041)	(0.002)
Industry FE	N	Y		N
Year FE	N	Y		N
Fama-MacBeth	N	N	Y	N
Observations	40,151	40,151	40,151	4235
R^2	0.342	0.448	0.353	0.186

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Table 12: **The effect of labor mobility on cash holdings**
Table 12 reports the coefficients of the regressions of cash holdings on labor mobility and control variables. The dependent variable is the ratio of cash and cash equivalents to assets. The sample is based on Compustat Annual Industrial files over the 1988-2011 period and it consists of 84,820 firm-year observations. Column 1 reports a pooled OLS regression with robust standard errors. Column 2 reports an OLS regression with year and industry fixed effects and standard errors clustered by year and industry. Column 3 reports a Fama-MacBeth regression with Newey and West (1987) standard errors to control for autocorrelation up to 5 lags. Column 4 reports a pooled OLS regression with mean values at 3-digit SIC industries and robust standard errors. Variable definitions are provided in the Table 2. For the fixed effects regression, I report within R^2. Standard errors are reported in parentheses. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)
1988-2011	OLS	FE	Fama-MacBeth	Industry
Dependent variable	Cash	Cash	Cash	Cash
Mobility	0.020***	0.015***	0.020***	0.008***
	(0.001)	(0.005)	(0.002)	(0.001)
Market-to-Book	0.016***	0.013***	0.019***	0.032***
	(0.000)	(0.001)	(0.003)	(0.003)
Firm Size	-0.003***	-0.005***	-0.006**	-0.017***
	(0.000)	(0.001)	(0.002)	(0.001)
Cash Flow	-0.059***	-0.038**	-0.040***	-0.019
	(0.004)	(0.016)	(0.008)	(0.022)
NWC	-0.335***	-0.335***	-0.333***	-0.221***
	(0.004)	(0.035)	(0.015)	(0.015)
Capex	-0.587***	-0.411***	-0.586***	-0.403***
	(0.009)	(0.075)	(0.045)	(0.039)
Book Leverage	-0.425***	-0.413***	-0.404***	-0.246***
	(0.003)	(0.034)	(0.016)	(0.016)
R&D	0.007***	0.006***	0.012***	0.031***
	(0.000)	(0.001)	(0.003)	(0.003)
Dividend Dummy	-0.049***	-0.029***	-0.046***	
	(0.001)	(0.007)	(0.003)	
Acquisitions	-0.330***	-0.291***	-0.349***	-0.291***
	(0.007)	(0.049)	(0.037)	(0.035)
IPO1	0.086***	0.085***	0.074***	
	(0.003)	(0.011)	(0.010)	
IPO2	0.040***	0.039***	0.038***	
	(0.003)	(0.007)	(0.004)	
IPO3	0.022***	0.023***	0.021***	
	(0.003)	(0.006)	(0.004)	
Industry Sigma	0.892***	0.190*	0.763***	0.248***
	(0.020)	(0.109)	(0.156)	(0.046)
Tangibility	-0.335***	-0.386**	-0325***	-0.231***
	(0.003)	(0.037)	(0.015)	(0.011)
Constant	0.343***		0.337***	0.229***
	(0.003)		(0.009)	(0.016)
Industry FE	N	Y		N
Year FE	N	Y		N
Fama-MacBeth	N	N	Y	N
Observations	84,820	84,820	84,820	4,304
R^2	0.531	0.565	0.542	0.602

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Table 13: **The effect of labor mobility on cash holdings: Labor Intensity**
Table 13 reports the coefficients of the regressions of cash holdings on labor mobility and control variables for the two subsamples of labor intensive and capital intensive firms. The dependent variable is the ratio of cash and cash equivalents to assets. The sample is based on Compustat Annual Industrial files over the 1988-2011 period. Columns 1 and 2 report a pooled OLS regression with robust standard errors. Columns 3 and 4 report an OLS regression with year and industry fixed effects and standard errors clustered by year and industry. Columns 5 and 6 report a Fama-MacBeth regression with Newey and West (1987) standard errors to control for autocorrelation up to 5 lags. Capital intensive firms are the firms in the bottom three deciles of the distribution of the number of employees over total assets, while labor intensive firms are the firms in the top three deciles of the distribution of the number of employees over total assets. Variable definitions are provided in the Table 2. For the fixed effects regression, I report within R^2. . Standard errors are reported in parentheses. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS		FE		Fama-MacBeth	
1988-2011	Labor Intensive	Capital Intensive	Labor Intensive	Capital Intensive	Labor Intensive	Capital Intensive
Dependent variable	Cash	Cash	Cash	Cash	Cash	Cash
Mobility	0.030***	0.007***	0.011***	0.000	0.028***	0.007***
	(0.002)	(0.001)	(0.004)	(0.007)	(0.002)	(0.001)
Market-to-Book	0.016***	0.012***	0.011***	0.011***	0.018***	0.014***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.003)	(0.003)
Firm Size	-0.004***	-0.001**	-0.009***	-0.003**	-0.007	-0.002***
	(0.001)	(0.000)	(0.003)	(0.001)	(0.005)	(0.001)
Cash Flow	-0.097***	-0.007	-0.058**	-0.002	-0.066***	-0.008
	(0.010)	(0.006)	(0.023)	(0.007)	(0.010)	(0.006)
NWC	-0.373***	-0.263***	-0.331***	-0.268***	-0.369***	-0.273***
	(0.011)	(0.005)	(0.042)	(0.022)	(0.020)	(0.019)
Capex	-0.191***	-0.115***	-0.087**	-0.087***	-0.213***	-0.115***
	(0.015)	(0.013)	(0.037)	(0.024)	(0.062)	(0.032)
Book Leverage	-0.372***	-0.322***	-0.325***	-0.330***	-0.351***	-0.319***
	(0.007)	(0.005)	(0.036)	(0.025)	(0.045)	(0.004)
R&D	0.005***	0.007***	0.003***	0.007***	0.009***	0.008***
	(0.000)	(0.001)	(0.001)	(0.001)	(0.003)	(0.002)
Dividend Dummy	-0.052***	-0.007***	-0.024**	-0.002	-0.050***	-0.007***
	(0.003)	(0.002)	(0.011)	(0.003)	(0.006)	(0.002)
Acquisitions	-0.385***	-0.305***	-0.325***	-0.251***	-0.392***	-0.313***
	(0.016)	(0.012)	(0.070)	(0.045)	(0.046)	(0.043)
IPO1	0.076***	0.050***	0.075***	0.047***	0.056***	0.048***
	(0.005)	(0.004)	(0.013)	(0.009)	(0.014)	(0.008)
IPO2	0.032***	0.019***	0.029***	0.018***	0.023***	0.019***
	(0.005)	(0.004)	(0.007)	(0.006)	(0.007)	(0.004)
IPO3	0.024***	0.005	0.021***	0.006**	0.015**	0.008**
	(0.005)	(0.003)	(0.006)	(0.002)	(0.007)	(0.003)
Industry Sigma	0.850***	0.212***	-0.068	0.067	0.848***	0.149
	(0.040)	(0.026)	(0.084)	(0.089)	(0.169)	(0.088)
Tangibility	-0.060***	-0.054***	-0.059***	-0.053***	-0.058***	-0.052***
	(0.002)	(0.002)	(0.007)	(0.005)	(0.005)	(0.004)
Constant	0.225***	0.195***			0.224***	0.199***
	(0.006)	(0.004)			(0.014)	(0.007)
Industry FE	N	N	Y	Y		
Year FE	N	N	Y	Y		
Fama-MacBeth	N	N	N	N	Y	Y
Observations	22081	25186	23913	27617	22081	25186
R^2	0.625	0.451	0.669	0.484	0.647	0.461

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
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Table 14: **The effect of labor mobility on the logarithm of cash holdings**
Table 14 reports the coefficients of the regressions of the logarithm of cash holdings on labor mobility and control variables. The dependent variable is the logarithm of the ratio of cash and cash equivalents to assets. The sample is based on Compustat Annual Industrial files over the 1988-2011 period and it consists of 77,105 firm-year observations. Column 1 reports a pooled OLS regression with robust standard errors. Column 2 reports an OLS regression with year and industry fixed effects and standard errors clustered by year and industry. Column 3 reports a Fama-MacBeth regression with Newey and West (1987) standard errors to control for autocorrelation up to 5 lags. Column 4 reports a pooled OLS regression with mean values at 3-digit SIC industries and robust standard errors. Variable definitions are provided in the Table 2. For the fixed effects regression, I report within R^2. Standard errors are reported in parentheses. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

	(1)	(2)	(3)	(4)
1988-2011	OLS	FE	Fama-MacBeth	Industry
Dependent variable	log(Cash)	log(Cash)	log(Cash)	log(Cash)
Mobility	0.121***	0.011	0.114***	0.062***
	(0.006)	(0.026)	(0.021)	(0.015)
Market-to-Book	0.088***	0.075***	0.116***	0.146***
	(0.003)	(0.013)	(0.017)	(0.020)
Firm Size	0.006**	-0.011	-0.004	-0.043***
	(0.003)	(0.016)	(0.003)	(0.013)
Cash Flow	-0.116***	-0.076	-0.030	0.313
	(0.024)	(0.063)	(0.040)	(0.198)
NWC	-2.287***	-2.229***	-2.214***	-2.691***
	(0.032)	(0.134)	(0.104)	(0.127)
Capex	-0.873***	-0.145	-0.997*	1.907***
	(0.095)	(0.231)	(0.516)	(0.464)
Book Leverage	-2.792***	-2.673***	-2.653***	-2.370***
	(0.025)	(0.169)	(0.223)	(0.133)
R&D	0.006***	0.004***	0.013**	0.089***
	(0.001)	(0.001)	(0.005)	(0.017)
Dividend Dummy	-0.228***	-0.089***	-0.234***	
	(0.012)	(0.035)	(0.026)	
Acquisitions	-2.282***	-1.929***	-2.216***	-5.001***
	(0.077)	(0.157)	(0.282)	(0.410)
IPO1	0.190***	0.227***	0.150***	
	(0.018)	(0.049)	(0.031)	
IPO2	0.068***	0.101**	0.055*	
	(0.019)	(0.045)	(0.028)	
IPO3	0.008	0.044	0.000	
	(0.021)	(0.043)	(0.031)	
Industry Sigma	4.622***	0.566	4.410***	1.913***
	(0.154)	(0.476)	(0.597)	(0.358)
Tangibility	-0.334***	-0.282***	-0.323***	-2.103***
	(0.007)	(0.036)	(0.033)	(0.116)
Constant	-2.165***		-2.217***	-1.336***
	(0.025)		(0.094)	(0.119)
Industry FE	N	Y	Y	N
Year FE	N	N	Y	N
Fama-MacBeth	N	N	N	N
Observations	77,105	77,105	77,105	4,304
R^2	0.383	0.435	0.382	0.457

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
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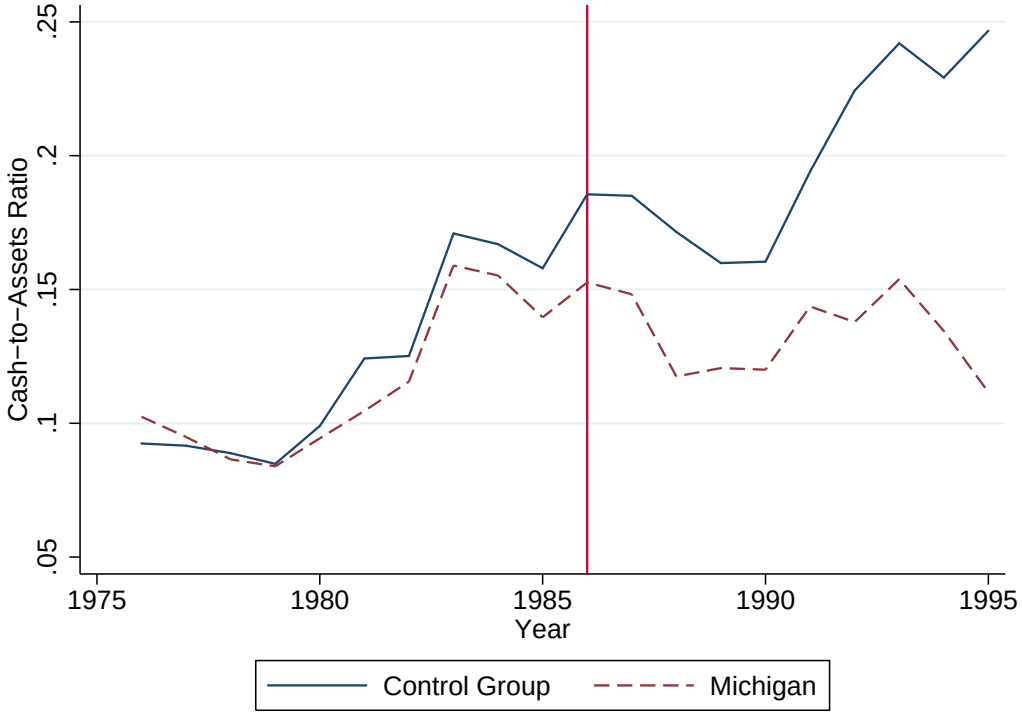
Table 15: **Cash Holdings and Labor Mobility: Robustness**
Table 15 reports two robustness tests. Panel A reports estimates the coefficients of the regressions of cash holdings on labor mobility separately for financially constrained and unconstrained firms. The dependent variable is the cash to assets ratio. The sample is split with respect to the intensity of financing constraint. I use three criteria to classify firm-year observations as constrained (C) or unconstrained (U): size, payout ratio and the Whited-Wu index. The sample is based on Compustat Annual Industrial files over the 1988-2011 period. Results are based on the sample split between constrained and unconstrained firms. I test for differences in coefficients across equations. Specifications do not include fixed effects. Panel B coefficient estimates of regressions that examine the effect of labor mobility and unioncoverage on cash holdings. Standard errors are reported in parentheses. The symbols ***, ** and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Panel A: Financial Constraints			
1988-2011	(1)	(2)	(3)
Criteria	Size	Payout Ratio	Whited-Wu
Unconstrained (U)	0.001	0.010*	0.006
	(0.001)	(0.006)	(0.005)
Constrained (C)	0.021***	0.021***	0.027***
	(0.006)	(0.002)	(0.006)
(C) - (U)	[0.00]	[0.00]	[0.00]

Panel B: Unions			
	(1)	(2)	(3)
1988-2011	OLS	FE	Fama-MacBeth
Dependent variable	Cash	Cash	Cash
Mobility	0.040**	0.028***	0.030**
	(0.016)	(0.007)	(0.017)
Union Coverage	-0.001***	0.001	-0.001***
	(0.000)	(0.001)	(0.000)
Controls	Y	Y	Y
Industry FE	N	Y	
Year FE	N	Y	
Fama-MacBeth	N	N	Y
Observations	24,279	24,279	24,279
R^2	0.621	0.633	0.615

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Figure 1: **Graphical Representation of Difference-in-Differences Analysis**
Figure 1 reports the time-series of the average cash holdings of firms located in Michigan (treated state) and in the control group (Alaska, California, Connecticut, Minnesota, Montana, North Dakota, Nevada, Oklahoma, Washington, and West Virginia).



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Chapter 2

Tick Size: Theory and Evidence

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Thick Size: Theory and Evidence

Francesco Consonni, Ingrid M. Werner,
Yuanji Wen, Barbara Rindi, Sabrina Buti*

July 2015

Abstract

We model a public limit order book where rational traders decide whether to demand or supply liquidity, and where liquidity builds endogenously. The model predicts that a reduction of the tick size will cause spreads and welfare to deteriorate for illiquid but improve for liquid books. We nd empirical support for these predictions based on European and U.S. data. The model also generates predictions for volume, but we nd less empirical support for these predictions which we attribute to opportunistic High-Frequency- Traders selectively entering the market.

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Tesi di dottorato "Essays in Empirical Finance"
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2.1 Introduction

Congress passed the Jumpstart Our Business Startup (JOBS) Act in 2012 in response to concerns that the U.S. market structure may not adequately support capital raising and secondary market liquidity for so called "emerging growth companies" (EGCs). The Act instructs the Securities and Exchange Commission (SEC) to evaluate whether changes to the U.S. market structure, specifically decimalization, contributed to the recent decline in Initial Public Offerings (IPOs) and adversely affected the liquidity for EGCs. Moreover, the JOBS Act allows the SEC to increase the minimum price variation – the tick size - if it is determined that EGCs should be traded and quoted in a larger tick size than one cent. While the SEC staff recommended against an increase in the tick size in its Report to Congress on Decimalization (2012), the Commission left the door open for future rulemaking based on the results from its proposed pilot study which is aimed at assessing the impact of the tick size on EGC liquidity.[1]

This renewed interest in the role the tick size may play in capital formation and secondary market liquidity motivates our study. The proponents of widening the tick size for EGCs argue that the reduction of the tick size to one penny was harmful for this group of stocks. In other words, they argue that one size does not fit all when it comes to setting the tick size. To understand whether or not different tick sizes for stocks with different characteristics are theoretically motivated, we first develop a model that explains how the tick size influences the incentives for market participants to supply liquidity. Specifically, we analyze the effects of a tick size reduction on spreads, depth, volume and welfare within the context of a Public Limit Order Book (PLB) that works like a double auction trading platform. Further, we evaluate a tick size reduction for books of different liquidity to address the question if one size fits all. We test the model's predictions

[1] See Federal Register Release No. 34-73448, File No. S7-24-89, November 3, 2014.

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by using both European and U.S. data. We conduct regression discontinuity tests which exploit that the tick size is adjusted dynamically as a function of stock price in European and U.S. markets. We also run cross-sectional Fama MacBeth regressions to examine the influence of the relative tick size on market quality for U.S. stocks.

To build our theoretical model, we extend Parlour's (1998) framework in several ways: we include more price levels on each side of the order book; and we allow each trader to decide whether to buy or sell based on their valuation. We generate liquidity endogenously by starting with an empty book and allowing liquidity to build as traders arrive. Allowing traders to determine whether to buy or sell, or not to trade, based on their valuation refines the strategy space and makes the analysis more realistic. We then use the model to study the effects of a change in the tick-to-price ratio on market quality and welfare. We consider two experiments: a change in the absolute tick size holding the price of the stock fixed; and a change in the price of the stock, holding the absolute tick size fixed. The first experiment generates empirical predictions about the effects of a change in the absolute tick size on market quality and welfare for a particular stock. The latter experiment generates predictions about market quality and welfare for stocks that trade with the same tick size but at different price levels. This experiment also generates predictions about a related topic: the effects of a stock split on market quality and welfare.

Our model shows that the effects of a tick size reduction depend on the liquidity of the book. For liquid books, a tick-size reduction increases competition among liquidity suppliers and even though depth at the best bid-offer decreases, aggregate depth increases, spread narrows, and as a result welfare improves. For illiquid books, instead, a tick-size reduction discourages liquidity provision and as a result depth declines and spread widens, and hence welfare deteriorates. Note

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that the improved market quality and welfare in the case of liquid books is associated with lower trading volume as traders switch from market to limit orders. By contrast, the deteriorating market quality and welfare for illiquid books is associated with higher trading volume as traders switch from limit to market orders. This underscores the importance of relying on an equilibrium theoretical model of a PLB when analyzing the effects of a tick size reduction on market quality.

Based on our model of a PLB, we therefore conclude that a smaller tick size is generally beneficial for liquid books as it results in narrower spreads, more total depth, and higher welfare – although this comes at the price of lower volume (and also lower inside depth). By contrast, for less liquid books, a larger tick size is generally preferable as it is associated with narrower spreads, higher inside and total depth, and higher welfare. However, note that the model predicts that a larger tick size for illiquid books is associated with lower trading volume. This may not be welcomed news for exchanges that derive a significant fraction of their revenue from trading fees. It is also unlikely to be what legislators had in mind when they hypothesized that a larger tick size would enhance liquidity. Nevertheless, assuming that the EGCs mentioned in the JOBS Act (2012) trade in a way that more closely resemble our illiquid books, our model lends support to the legislators' conjecture that the optimal tick size for EGCs may be larger than the optimal tick size for more liquid stocks. In other words, there is indeed support for the idea that one size does not fit all when it comes to the tick size.

We also find that a change in the absolute tick size holding price constant, and a change in the price that results in the same change in the tick to price ratio are equivalent. In other words, the effects of changing price (while holding price constant) on market quality and welfare are identical to those described above with the important caveat that the quoted spread will be different. Specifically, consider comparing a doubling of a stock price holding the tick constant to cutting

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the tick size in half. A doubling of the stock price will result in an absolute quoted spread that is twice as large as the absolute quoted spread would be after the tick size is cut in half. Similarly, after a two-for-one stock split the model predicts that the absolute quoted spread will be half as large as it would be after a doubling of the tick size.

Our model highlights that when setting the tick size, regulators and exchanges face a fundamental trade-off between the effects on market quality and welfare and the effects on volume. More precisely, we find that welfare tends to be inversely related to the quoted spread but not necessarily positively related to depth. For liquid books a substantial reduction in the tick size improves spreads and welfare, but this comes at the price of reduced trading volume. Similarly, a reduction in the tick size for illiquid books deteriorates spreads and welfare, but is associated with an increase in trading volume. The reason for this trade-off is that traders in our model optimally choose whether to use market or limit orders, and at which prices to post limit orders. When traders switch from market to limit orders, fewer trades take place. Conversely, when traders switch from limit to market orders, more trades occur. This is a fundamental insight that highlights the importance of building models where liquidity arises endogenously through optimal order submission strategies adopted by rational traders.

We test the theoretical predictions concerning the effects of a tick-size reduction on quoted spreads, depth and volume based on a sample of U.K. listed stocks that experience regular tick-size changes. Specifically, on the London Stock Exchange (LSE), the tick size changes dynamically when a stock price crosses certain thresholds. The threshold and tick-size schedule vary by market segment and price. The segments we study are SET1 and STMM and the price thresholds are 10 GBX, 100 GBX and 500 GBX.[2] For example, for SET1 stocks, the tick size is

[2]Because British stocks are traded in pence we report the stock price in pence sterling, i.e.,GBX.

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0.1 GBX when the price is below 500 GBX and 0.5 GBX when the price is above 500 GBX (but below 1000 GBX). So, when a stock price moves from 499 GBX to 500 GBX, the tick size increases by a factor of five. For inclusion in our sample, we require that a stock crosses the relevant threshold at least once, and that it is part of a FTSE 100 Index (for SET1 stocks) or FTSE 250 Index (for STMM stocks) to ensure sufficient trading on each side of the threshold.

By construction, the stocks in our LSE sample are liquid and we therefore compare the results to the model's predictions about liquid books. Our model predicts that when the stock price for a liquid book moves from below to above a threshold, there is a discrete increase in the absolute tick size and we should see an increase in both the quoted spread and inside depth and an increase in volume. We use a regression discontinuity framework to test these predictions. The results for the most liquid SET1 stocks support the model's predictions for quoted spread and depth both for the 500 GBX and the 1000 GBX thresholds. The results are weaker for the less liquid STMM stocks, especially for quoted spread, but the results generally go in the right direction. We do not find empirical support for an increase in volume as the stock price moves across a threshold and the spread therefore widens. We discuss the volume puzzle further below.

While most U.S. stocks trade with a tick size of \$0.01, stocks priced below \$1.00 trade at a lower tick size, \$0.0001. When a U.S. stock's price moves from below to above \$1.00, the tick size therefore increases by a factor of 100. We construct a sample of U.S. stocks that cross the \$1.00 threshold, and repeat the RDD tests discussed above also for this sample. Compared to the LSE sample, these U.S. stocks are less liquid. Nevertheless, the results show that both the quoted spread and inside depth increase significantly when the tick size increases from \$0.0001 to \$0.01, confirming the results from the LSE. We also find that consolidated volume for U.S. stocks increases when price moves from below to

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above the $1.00 threshold as predicted by our model. However, the increase in volume is not statistically significant.

Finally, we test the model's predictions regarding the effect of changes in price for a given tick size based on a stratified sample of NYSE and Nasdaq stocks. Specifically, we sort all NYSE stocks into terciles by market capitalization and price, and form nine mutually exclusive groups. We sample 10 stocks randomly from each group. The procedure is repeated for Nasdaq stocks, but note that we use NYSE breakpoints so that the samples are comparable across exchanges. Our final sample includes 180 stocks. Note that there is no variation in the absolute tick size for this sample - all stocks trade with a $0.01 minimum price increment. Hence, the entire variation in relative tick size comes from cross-sectional differences in stock price. We run daily cross-sectional Fama MacBeth regressions to test whether the estimated effect of the price level (which is inversely related to the relative tick-size) on the absolute quoted spread, inside depth and volume support our model predictions. For completeness, we also examine the relationship between the stock price and the relative spread. We follow the market microstructure literature and control for other factors that have been shown to influence quoted spread and depth such as volume, order imbalance, and volatility. Similarly, in the volume regressions we control for quoted spread, order imbalance, depth, and volatility.

Our theoretical model predicts that a lower relative tick size caused by an increase in the stock price should for a liquid book be associated with both lower depth and wider quoted spread. Our empirical results support this prediction both for the full sample and for sub-samples by market capitalization and stock price. Specifically, the stock price is significantly negatively related to depth controlling for listing exchange, volume, absolute spread, order imbalance and volatility. Moreover, the stock price is significantly positively related to the absolute quoted spread, controlling for listing exchange, volume, depth, order imbalance,

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and volatility. By contrast, our model predicts that a lower relative tick size should for liquid books be associated with a narrower relative spread and lower volume but this prediction is not supported by the stratified sample of U.S. stocks. Instead, we find that both realized spreads and volume actually increase, which is consistent with the model's prediction for illiquid books. Moreover, this is true overall as well as in subsamples, and is robust to altering the set of control variables. The economic magnitudes of the changes in relative spreads are small and therefore less bothersome, but that is not the case for changes in volume.

Hence, we fail to find support for our model's prediction that a lower tick size is associated with lower volume. Our model assumes that traders are drawn from a given distribution parameterized by their level of impatience. However, the model does not allow other groups of traders to join the market following a market structure change. In practice, it is likely that there are traders on the side-lines with latent demand for trading for whom trading opportunities look attractive after a tick size change. Our empirical finding that volume increases following a tick size reduction suggests that the population of traders changes following a tick size reduction. Specifically, it is possible that traders, e.g., High Frequency Traders (HFTs), are drawn to the market following a tick size reduction because their quote-matching trading strategies are profitable with a lower tick size. We elaborate on this conjecture in the conclusions.

This paper is related to three strands of the existing theoretical literature: the literature on inter-market competition, the literature on the optimal tick size, and the literature on internalization of order flow by broker dealers (Battalio and Holden, 2001). To the best of our knowledge, it is the first model that allows researchers to investigate the role of both absolute and relative tick size in a multi-period limit order market. We also believe that it is the first theoretical framework that takes into account the liquidity of the limit order book.

Tesi di dottorato "Essays in Empirical Finance"
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Empirically, our paper contributes to the literature on the tick size by studying the effect of tick-size changes in the context of a regression discontinuity design based on a sample of European stocks and a sample of U.S. stocks for which there are regular tick size changes as prices move across well-defined thresholds. We also re-examine the effects of the relative tick size for a more recent stratified sample of U.S. stocks. In related work, O'Hara, Saar, and Zhong (2014) study the relationship between the relative tick size and measures of liquidity for NYSE stocks. Instead of cross-sectional regressions they use a matched sample methodology. Like us, they find that a larger relative tick size is associated with more depth at the inside but unlike us they find no significant effect on spreads.

The remaining part of this paper is structured as follows: in Section 2 we overview the related literature; in Section 3 and 4, we focus on the single market model, whereas Section 5 contains the model with inter-market competition. We present the empirical implications in Section 6, and the empirical analysis in Section 7. We draw policy conclusions in Section 7. All the proofs appear in the Appendix.

2.2 Literature Review

There is extensive research on the relationship between the reduction of the tick size and market quality.

Theoretical models have been developed to study the effect of a tick size variation in different market structures. Seppi (1997) investigates the optimal tick size in a market in which a specialist competes for liquidity provision against a competitive limit order book and finds that large traders may prefer a larger tick size than small traders. Cordella and Foucault (1999) study competition between dealers who arrive at the market sequentially and whose bidding strategy depends

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of the value of the tick size. They show that a larger tick size can increase the speed at which dealers adjust their quotes towards the competitive price, especially when monitoring costs are high. Hence transaction costs can ultimately decrease following an increase in the tick size. Similarly, competition among dealers for the provision of liquidity to an incoming market order drives the results obtained by Kadan (2006). He shows that when the number of dealers is small, a small tick size is associated with higher liquidity since this prevents dealers from exploiting their market power. When the number of dealers is instead large, a small tick size may also improve liquidity. The reason is that a small tick size allows dealers to post quotes as close as possible to their reservation value, thus transferring welfare to liquidity demanders.

Our model departs from all these protocols by considering a pure order driven market in which liquidity provision is endogenously created by market participants who choose limit as opposed to market orders. To evaluate the effects of a tick size variation in pure limit order markets, one has to consider the competitive interaction of both patient traders who supply liquidity via limit orders, and impatient traders who demand liquidity via market orders. Our framework shares this feature with the dynamic model of Foucault, Kadan and Kandel (2005) who show that a reduction of the tick size may harm market resiliency and have adverse effects on transaction costs. In their model, however, traders cannot refrain from trading and when submitting limit orders they must provide a price improvement. Hence, because patient traders cannot join the queue at the existing best bid or offer, a larger tick size has the effect of making their orders more rather than less aggressive, resulting in an increased resiliency and a narrower spread. By contrast, in our model traders are free to submit market and limit orders at any level on the price grid, as well as to refrain from trading.

Our protocol is closer to Goettler, Parlour and Rajan (2005) who consider

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an infinite horizon version of Parlour (1998) and model a limit order book as a stochastic sequential game with rational traders submitting orders at, above or below the existing best quotes. Goettler et al. (2005) show that, by reducing the tick size, traders switch from limit to market orders so that the total surplus of investors increases. We show instead that the effects of a tick size variation depend on the magnitude of the tick size change and on the liquidity of the limit order book. Differently from Goettler et al. (2005), we model a large tick size reduction without moving the trading crowd towards the spread. We also do not assume that after the tick size reduction the asset value coincides with one of the levels on the new price grid. It is perhaps for these reasons that we do not find that traders necessarily become more aggressive following a tick size reduction, but rather that traders' choice between limit and market orders depend on the state of the book.

Empirical studies from various markets around the world have found that a tick size reduction is associated with a decline in both the spread and depth, and that the spread is not equally affected across stocks.[3] These findings are confirmed by a more recent pilot program implemented by the major European platforms aimed at investigating the effect of a reduction of the tick size, and are consistent with the early predictions of Angel (1997) and Harris (1994).[4]

Finally, this paper is related to the literature on broker dealers' internalization and payment for order flow.[5] Chordia and Subrahmanyam (1995) and Kandel and

[3]See for example Ahn et al. (1996), Bacidore (1997), Bacidore, Battalio, and Jennings (2003), Bessembinder (2000 and 2003), Bollen and Busse (2006), Bourghelle and Declerck (2004), Chakravarty, Panchapagesan, and Wood (2005), Goldstein and Kavajecz (2000), Griffiths et al. (1998), and Ronen and Weaver (2001).

[4]In December 2008, BATS Europe, in conjunction with Chi-X, Nasdaq OMX Europe and Turquoise, developed a proposal to standardize the tick size of the pan European trading platforms. Starting June 1, 2009, Chi-X, followed by Turquoise, BATS Europe, and finally the LSE and Nasdaq OMX Europe, reduced the tick size for a number of stocks. This pilot program, aimed at studying the effect of a change in the tick size based on actual market data, showed that following the reduction of the tick size, effective spread, inside spread, inside depth and average trade size decreased (BATS, 2009).

[5]Internalization is either the direction of order flows by a broker-dealer (BD) to an affiliated specialist, or the execution of order flows by that BD acting as a market maker.

Tesi di dottorato "Essays in Empirical Finance"
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Marx (1999) show that these practices arise from the existence of a positive tick size. By contrast, Battalio and Holden (2001) show that when the tick size is set equal to zero, brokers still internalize their clients' orders as they make profits by exploiting their direct relationships with customers. This prediction is consistent with the related empirical work.[6]

2.3 The Model

In this paper we address two fundamental issues regarding the tick size. First, we investigate what are the effects of a change in the tick size on market quality and agents' welfare. Second, given that it is the relative tick size rather than the absolute value of the tick size that matters for market participants, we aim to understand whether a change in tick size is equivalent to a change in the stock price.

To investigate the effects of a tick size reduction, we develop a model where sequentially arriving risk neutral traders have access to a public limit order book. The model extends Parlour (1998) to include two levels of discrete prices on the bid and the offer side of the market; we also add a tick size (or asset value) shock, and finally we allow investors to choose the direction of their trades.

2.3.1 The Market

A market for a security is run over a trading day divided into 4 periods, $t = \{t_1, t_2, t_3, t_4\}$. At each period t a trader arrives. Following Parlour (1998), we assume that the order size is unitary and that each trader who comes to the market is characterized by a parameter indicating his personal valuation of the asset, β,

[6] See Chung et al. (2004), Hansch et al. (1999), He et al. (2006), Hendershott and Jones (2005), and Porter and Weaver (1997).

Tesi di dottorato "Essays in Empirical Finance"
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which is drawn from the uniform distribution $U(\underline{\beta}, \overline{\beta})$, with $0 \leq \underline{\beta} < 1 < \overline{\beta}$. The parameter β can also be interpreted as the trader's degree of impatience. As we discuss below, a trader with a β close to either $\underline{\beta}$ or $\overline{\beta}$ has an extreme valuation of the asset and is more eager to trade, whereas a trader with a personal valuation β close to 1 is more patient. For all of our numerical simulations and the analytical solution to the model we assume that the support of the β distribution is $U(0, 2)$.

Upon arrival in period t, the trader observes the state of the book, which is characterized by the number of shares available at each level of the price grid. To investigate how changes in the tick size affect traders' aggressiveness in the provision of liquidity as well as depth at different levels of the book, we need at least two price levels on each side of the PLB. Therefore we extend Parlour's (1998) model to include two prices on the ask ($A_1 < A_2$) and two prices on the bid side of the market ($B_1 > B_2$), symmetrically distributed around the asset value v. The difference between two adjacent prices -the minimum price increment- is the tick size which also corresponds to the minimum inside spread. In this general framework we set the tick size equal to a constant, τ. Thus the possible price levels are equal to $A_1 = v + \frac{\tau}{2}$, $A_2 = v + \frac{3\tau}{2}$, $B_1 = v - \frac{\tau}{2}$, and $B_2 = v - \frac{3\tau}{2}$ The state of the book that specifies the number of shares Q_t available at each price level is defined as $S_t = [Q_t^{A_2}, Q_t^{A_1}, Q_t^{B_1}, Q_t^{B_2}]$. As in Seppi (1997) and Parlour (1998) we assume that a trading crowd provides liquidity at the highest and lowest price levels of the limit order book. This liquidity provision prevents traders from quoting prices that are too far away from the top of the book. In addition, incoming traders are allowed to submit limit orders that queue up in front of the trading crowd.

In this market, which enforces price and time priority, traders can choose between two types of orders that cannot be modified or cancelled after submission: limit orders that we indicate by $+1$, and market orders that we indicate by -1. We define H_t a trader's strategy at time t. Traders can submit limit orders to sell

Tesi di dottorato "Essays in Empirical Finance"
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or to buy one share respectively at the two levels of the ask and of the bid side of the book, $H_t = \{+1^{A_k}, +1^{B_k}\}$, where $k = 1, 2$. These orders stay on the book until they are executed against a market order of opposite sign. Alternatively, traders can submit market orders which hit the best bid or ask prices available on the book and are hence executed immediately, $H_t = \{-1^{B_{k'}}, -1^{A_{k'}}\}$, where $k' = 1, 2$ refers to the best price. Finally, traders can decide not to trade, $H_t = \{0\}$. The trader's strategy space is therefore $H_t = \{-1^{A_{k'}}, +1^{A_k}, 0, +1^{B_k}, -1^{B_{k'}}\}$. The change in the limit order book induced by the trader's strategy H_t is indicated by h_t and defined as:

$$h_t = [h_t^{A_2}, h_t^{A_1}, h_t^{B_1}, h_t^{B_2}] = \begin{cases} [\pm 1, 0, 0, 0] & \text{if } H_t = \pm 1^{A_2} \\ [0, \pm 1, 0, 0] & \text{if } H_t = \pm 1^{A_1} \\ [0, 0, 0, 0] & \text{if } H_t = 0 \\ [0, 0, \pm 1, 0] & \text{if } H_t = \pm 1^{B_1} \\ [0, 0, 0, \pm 1] & \text{if } H_t = \pm 1^{B_2} \end{cases} \tag{1}$$

The state of the book is hence characterized by the following dynamics:

$$S_t = S_{t-1} + h_t \tag{2}$$

where S_{t-1} is the state of the book that the trader arriving at t observes before he submits his order, and S_t is the state of the book after his order submission. We assume that when a trader arrives at t_1 he observes the initial state of the book denoted by S_0, which is by assumption empty.[7]

[7] Starting with a book that displays some liquidity would be straightforward. In Buti, Rindi, Wen and Werner (2011) we compare books that opened either empty or with 1 or 2 shares on the different levels of the price grid. We here start with an empty book so that we can compare books with different degree of endogenous rather than exogenous liquidity. Results do not qualitatively change.

Tesi di dottorato "Essays in Empirical Finance"
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2.3.2 Order Submission Decision

To select his order submission strategy, a trader needs to choose an order type and, if he chooses to submit a limit order, a price. His goal is to maximize utility, which in this risk neutral setting is equivalent to maximize his payoff, considering all the available strategies. Market orders guarantee immediate execution, while limit orders enable traders to obtain a better price. When traders choose a limit rather than a market order, they increase their non-execution costs as, to potentially obtain a better price, they forgo execution certainty. At the same time, however, they reduce their price opportunity cost, which is the cost associated with an execution at a less favorable price. Hence in this market traders face the trade-off between non-execution costs (NEC) and price opportunity costs (POC). The payoffs of the different strategies available to traders, $U(\cdot)$, are listed in Table 1.

[**Insert Table 1 here**]

Market orders are always executed at the best ask or bid price and their payoff depends on the traders' personal valuation of the asset β. Limit orders' payoff also depends on the execution probability that we denote $p_t(A_k|_{S_t})$ and $p_t(B_k|_{S_t})$ for a limit sell and for a limit buy order respectively submitted at the ask price A_k, or at the bid price B_k. As mentioned before, in our model the trader's own β can also be interpreted as his degree of impatience**.** If a trader comes to the market with an extreme personal valuation, his non-execution costs are higher compared to those of a trader with a β around 1, who is instead more concerned about the price opportunity costs. For this reason, the first trader will be more incline to opt for a market order and therefore he will be more likely to want to buy or sell the asset immediately. Note also that we relax Parlour's (1998) assumption that nature exogenously selects buyers and sellers at the beginning of each trading

Tesi di dottorato "Essays in Empirical Finance"
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period. Hence, for example, a trader with a personal valuation next to 2 would opt for a market buy order, rather than refrain from trading as would happen in Parlour's model had nature selected him as a seller.

Figure 1 shows the extensive form of the game and $S_0 = [0, 0, 0, 0]$ is the opening state of the book at t_1. Assume that a trader arriving at the market at t_1 decides to submit a limit sell order at A_2, $H_{t_1} = +1^{A_2}$. The execution probability of this order depends both on the initial state of the book and on the future orders submitted by the other market participants. Because before submission no shares were standing at A_1 and A_2, this order is at the top of the queue on the sell side and would be executed as soon as a market buy order arrives in the following periods t_2, t_3 or t_4. However, the execution probability of this order will decrease if a trader arrives in period t_2 and gains price priority by submitting a limit sell order at A_1, $H_{t_2} = +1^{A_1}$. Figure 1 shows that a limit sell order at A_1 is one of the possible strategies of a trader arriving at t_2. If this order is actually chosen by the incoming trader, then at t_3 the book will open with one share at both the first and the second level of the ask side, $S_{t_2} = [1, 1, 0, 0]$, and only the order posted at A_1 will have positive execution probability at t_3. If this order is indeed executed at t_3, then the order previously posted at A_2 may be executed at t_4, provided that a market order to buy arrives at t_4. Recall that only one trader arrives at each trading round.

Figure 1 focuses on the ask side, but the order execution probability also depends on the state of the other side of the book. For instance, a deep book on the bid side increases the incentive for a seller to post limit orders as he knows that incoming buyers will be more inclined to post a market rather than a limit order, due to the long queue on the bid side. This interaction between different levels of the two sides of the market is crucial for our model, and is another way in which our model extends the work of Parlour (1998).

Tesi di dottorato "Essays in Empirical Finance"
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[**Insert Figure 1 here**]

2.3.3 Market Equilibrium

Traders use information from the state of the limit order book to rationally compute the execution probabilities of different orders. Having done so, they are then able to choose the optimal strategy consistently with their own β by simply comparing the expected payoff from each order.

We solve the model by backward induction. At time t_4, the execution probability of limit orders is zero, and traders will therefore only either submit market orders or decide not to trade. It is easy to show that traders' equilibrium strategies are:

$$H^*_{t_4}(\beta|_{S_{t_3}}) = \begin{cases} -1^{B_{k'}} & \text{if } \beta \in [0, \frac{B_{k'}}{v}) \\ 0 & \text{if } \beta \in [\frac{B_{k'}}{v}, \frac{A_{k'}}{v}) \\ -1^{A_{k'}} & \text{if } \beta \in [\frac{A_{k'}}{v}, 2] \end{cases} \tag{3}$$

By using these equilibrium strategies together with the distribution of β, we calculate the equilibrium execution probabilities of limit orders submitted at t_3 that are the dynamic link between period t_4 and t_3:

$$p^*_{t_3}(A_k|_{S_{t_3}}) = \begin{cases} \int_{\beta \in \{\beta: H^*_{t_4} = -1^{A_{k'}}\}} \frac{1}{2} d\beta = 1 - \frac{A_{k'}}{2v} & \text{if } A_k = A_{k'} \text{ and } Q^{A_k}_{t_3} = 0 \\ 0 & otherwise \end{cases} \tag{4}$$

$$p^*_{t_3}(B_k|_{S_{t_3}}) = \begin{cases} \int_{\beta \in \{\beta: H^*_{t_4} = -1^{B_{k'}}\}} \frac{1}{2} d\beta = \frac{B_{k'}}{2v} & \text{if } B_k = B_{k'} \text{ and } Q^{B_k}_{t_3} = 0 \\ 0 & otherwise \end{cases} \tag{5}$$

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
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Because there is only one period left in the trading game, the execution probability of a limit order submitted at t_3 is positive only if the order is posted at the best ask ($A_{k'}$) or bid price ($B_{k'}$), and if there are no other orders already standing in the book at that price. As an example, here we discuss the equilibrium strategies for the book opening with room for limit orders on both sides of the market, i.e., $p^*_t(A_k|S_t) \neq 0$ and $p^*_t(B_k|S_t) \neq 0$.[8] The trader's optimal strategies are:

$$H^*_{t_3}(\beta|_{S_{t_2}}) = \begin{cases} -1^{B_{k'}} & \text{if } \beta \in [0, \beta_{-1^{B_{k'}},+1^{A_k},t_3|_{S_{t_2}}}) \\ +1^{A_k} & \text{if } \beta \in [\beta_{-1^{B_{k'}},+1^{A_k},t_3|_{S_{t_2}}}, \beta_{+1^{A_k},+1^{B_k},t_3|_{S_{t_2}}}) \\ +1^{B_k} & \text{if } \beta \in [\beta_{+1^{A_k},+1^{B_k},t_3|_{S_{t_2}}}, \beta_{+1^{B_k},-1^{A_{k'}},t_3|_{S_{t_2}}}) \\ -1^{A_{k'}} & \text{if } \beta \in [\beta_{+1^{B_k},-1^{A_{k'}},t_3|_{S_{t_2}}}, 2] \end{cases} \tag{6}$$

where

$\beta_{-1^{B_{k'}},+1^{A_k},t_3|_{St2}} = \frac{B_{k'}}{v} - \frac{p^*_{t3}(A_k|_{S_{t_3}})}{1-p^*_{t3}(A_k|_{S_{t_3}})} \cdot \frac{A_k - B_{k'}}{v}$, $\beta_{+1^{A_k},+1^{B_k},t_3|_{S_{t_2}}} = \frac{p^*_{t_3}(A_k|_{S_{t3}})A_k + p^*_{t3}(B_k|_{S_{t_3}})B_k}{p^*_{t_3}(A_k|_{S_{t_3}}) + p^*_{t_3}(B_k|_{S_{t_3}})} \cdot \frac{1}{v}$, and $\beta_{+1^{B_k},-1^{A_{k'}},t_3|_{St2}} = \frac{A_{k'}}{v} + \frac{p^*_{t_3}(B_k|_{S_{t_3}})}{1-p^*_{t_3}(B_k|_{S_{t_3}})} \cdot \frac{A_{k'} - B_k}{v}$.

These thresholds are derived by taking into account that the trader arriving at the beginning of period t_3 observes the state of the book S_{t_2}. For instance $\beta_{-1^{B_{k'}},+1^{A_k},t_3|_{S_{t_2}}}$ denotes the threshold between a market sell order hitting the best bid price, $B_{k'}$, and a limit sell order posted at the ask price A_k, and it is derived by equating the payoffs of the two orders. Note that the greater the limit order execution probability, $p^*_{t_3}(A_k|_{S_{t_3}})$, the smaller this threshold and the higher will the probability that traders choose limit rather than market orders be.

More generally, if the execution probability at time t is high enough for non-execution costs to be lower than price opportunity costs, the trader will submit a limit order. If instead the execution probability is low, he will choose a market order. This trade-off crucially depends on the value of the tick size, τ, and on the

[8] We refer to the Appendix for a more detailed discussion.

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
discussa presso Università Commerciale Luigi Bocconi-Milano nell'anno 2016
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price of the stock, v.

When a trader chooses a limit order, he also has to decide how aggressively to price this order relative to v. The optimal price at which a trader submits a limit order is once more the result of the trade-off between non-execution costs and price opportunity costs: a more aggressive price implies a higher execution probability due to both the lower risk of being undercut by incoming traders and the fact that the order becomes more attractive for traders on the opposite side of the market. However, this is obtained at the cost of lower profits once the order is executed.

From the equilibrium strategies at t_4, we can derive the execution probabilities for limit orders submitted at t_3 and the corresponding equilibrium strategies**.** Due to the recursive structure of the game and because traders are indifferent between orders with a zero execution probability, a unique equilibrium always exists and is defined as follows:

Definition 1 *An equilibrium is a set of order submission decisions* $\{H_t^*\}$ *and states of the limit order book* $\{S_t\}$ *such that at each period the trader maximizes his payoff* $U(\cdot)$ *according to his Bayesian belief over the execution probabilities* $p^*(\cdot)$*, i.e.,*

$$\{H_t^* := \arg\max\ U(\cdot|_{S_{t-1}})\}$$
$$\{S_t := S_{t-1} + h_t^*\}$$
where h_t^* *is defined by (1)*

In our numerical simulations we assume that $\tau = \{0.1, \frac{0.1}{3}\}$ and $v = \{1, 3\}$. In the Appendix we show that our equilibrium is robust to different parameter specifications provided that the tick size relative to the asset value is not too large, i.e., $\frac{\tau}{v} \in (0, 0.1]$. Within this range the monotonicity of the β thresholds with respect to the relative tick size is guaranteed.

Tesi di dottorato "Essays in Empirical Finance"
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2.4 Tick Size Reduction

Our next task is to study the effect on market quality and welfare of a tick size reduction in the context of a PLB. Our approach is to compare the equilibrium trading strategies from a large tick size market (LM) with a tick size equal to $\tau_{LM} = \tau$ with those obtained from a market (SM) that opens at t_1 with the same large tick equal to τ, and then at t_2 has the tick size substantially decreased to $\tau_{SM} = \frac{\tau}{3}$.[9] The choice of a tick size change is not neutral. The choice of the initial price and tick size grid defines an intital price improvement (PI) that is obviously proportional to the asset value. For example starting with $v = 1$, $\tau = 0.1$, and 4 price levels, we are implicitly assuming that the investors' range of price improvement $(A_2 - B_2)$ is equal to 3 ticks, which corresponds to 30% of v. For the change in the tick size to be neutral, the PI must be held proportional to the asset value throughout the different model specifications considered. We assume that at t_1 the market opens with the new price grid and as before we compare results from different states of the book at t_2.

The price grids are shown in Table 2: on the LM the price grid is $\{A_2, A_1, B_1, B_2\}$; on the SM from period t_2 onward it has five levels on both the ask and the bid side, a_l and b_l, with $l = 1, .., 5$.

[**Insert Table 2 here**]

Given that the evolution of the state of the book is characterized by equation

[9] The choice of the value $\tau_{SM} = \frac{\tau}{3}$ is purely technical. This value is consistent with an additional price level between A_1 and B_1 on both sides of the market. At the same time it guarantees that there are four price levels on the SM grid (namely a_2, b_2 and a_5, b_5) that coincide with A_1, B_1 and A_2, B_2. In this case the new tick size grid fits perfectly into the old one. The tick size redution can be either anticipated or unanticipated. If traders do not anticipate the tick size reduction, they trade somewhat less aggressively at t_1, but the equilibrium states of the book at the end of t_1 do not change and consequently equilibrium strategies at t_2 do not change either.

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(2), the expected states of the book for the LM and the SM are given by:

$$E_{t-1}[S_t^{LM}] = S_{t-1}^{LM} + E[h_t^{LM}] \quad (7)$$

$$E_{t-1}[S_t^{SM}] = S_{t-1}^{SM} + E[h_t^{SM}] \quad (8)$$

where $E[h_t^{LM}]$ is the vector with elements $E[h_t^i] = \int_{\beta \in \{\beta : H_t(\beta) = \pm 1^i, 0\}} H_t^{LM}(\beta) \frac{1}{2} d\beta$ with $i = A_k, B_k$, and $E[h_t^{SM}]$ the vector with elements $E[h_t^j] = \int_{\beta \in \{\beta : H_t^{SM}(\beta) = \pm 1^j, 0\}} H_t^{SM}(\beta) \frac{1}{2} d\beta$ with $j = a_l, b_l$. The main difference between the LM and SM markets is that from period t_2 onward in the SM both S_t^{SM} and h_t^{SM} consist of ten components rather than four. In other words, the trader's strategy space for the SM is much richer thanks to the finer price grid: $H_t^{SM} = \{\pm 1^j, 0\}$.

To compare the two markets and assess the effects of a change in the tick size, we build standard indicators of market quality and we measure expected welfare based on traders' equilibrium strategies.

For each period t, depth is measured as the number of shares available on the book at different price levels. More precisely, for the LM we define the following two depth indicators:

$$DBBO_t^{LM} = E[Q_t^{A_{k'}} + Q_t^{B_{k'}}] \quad (9a)$$

$$AgDP_t^{LM} = E[\textstyle\sum Q_t^i] \quad (9b)$$

where $DBBO_t^{LM}$ is the average of the sum of the depth at the best quotes, and $AgDP_t^{LM}$ is the aggregate depth measured by the sum of the average of the depth at all price levels. The average inside spread, SP_t, is computed as the expected difference between the best ask and the best bid prices:

$$SP_t^{LM} = E[A_{k'} - B_{k'}] \quad (10)$$

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Finally, volume in period t is measured by the number of orders executed, while liquidity provision is measured by the number of limit orders submitted. Because at each period only one trader arrives, expected volume, VL_t, and liquidity provision, LP_t, are computed as the probability that a trader submits respectively a market order or a limit order at all price levels:

$$VL_t^{LM} = E[\sum_i \int_{\beta \in \{\beta: H_t = -1^i\}} 1 d\beta] \quad (11)$$

$$LP_t^{LM} = E[\sum_i \int_{\beta \in \{\beta: H_t = +1^i\}} 1 d\beta] \quad (12)$$

Indicators of market quality for the SM are computed in a similar way, but using $j = \{a_{1:5}, b_{1:5}\}$.

Following Degryse et al. (2009) and Goettler et al. (2005), we measure expected welfare in each period, $E(W_t)$, as the sum of the agents' expected gains from both market orders (first term) and limit orders (second term):

$$E(W_t) = \sum_i \int_{\beta \in \{\beta: H_t = -1^i \big|_{S_{t-1}}\}} |i - \beta v| \cdot f(\beta) d\beta + \sum_i \int_{\beta \in \{\beta: H_t = +1^i \big|_{S_{t-1}}\}} |i - \beta v| \cdot p_t^*(i \,|_{S_t}) \cdot f(\beta) d\beta \quad (13)$$

We use our measure of welfare to investigate how the change in the gains from trade that a smaller tick size entails translates into a change in the welfare of market participants.

2.4.1 Effects on Market Quality and Welfare

Because market quality depends on the state of the book, we compare the initial LM with the SM in the second period of the trading game conditional on the opening state of the book. More precisely, the two markets start empty at the beginning of the game and depending on the type of orders posted by traders in period t_1, they may open with some depth on the different levels of the book at

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t_2. By comparing the equilibrium states of the book at the end of period t_2 we are therefore able to compute and compare the indicators of market quality "y" for the LM with the same indicators of market quality for the SM under different scenarios for the opening state of the book at t_2 that proxy for stocks with different degrees of liquidity:

$$\Delta y_{t_2} = [y_{t_2}^{SM} - y_{t_2}^{LM}]|_{S_{t_1}} \tag{14}$$

where $y_{t_2} = \{DBBO, AgDP, SP, VL, LP\}$.

To study the change in welfare following a reduction of the tick size we compare traders' expected welfare in the LM, $E(W_t^{LM})$, with that in the SM, $E(W_t^{SM})$, during the second period of the trading game, t_2:

$$\Delta W_{t_2} = E[W_{t_2}^{SM} - W_{t_2}^{LM}]|_{S_{t_1}} \tag{15}$$

In particular to illustrate the effects of different tick sizes on both liquid and illiquid books, we consider two equilibrium states of the book at the end of period t_1 (i.e., beginning of t_2): an empty book which is our proxy for an illiquid stock, and a book with one unit on the first (second) level of the LM (SM) price grid which is our proxy for a liquid stock.[10] We present results for period t_2 as this is the period with the longest horizon given that the book at least may be non-empty.

[10] When the book opens empty at t_1, in the LM, the SM traders choose among three equilibrium strategies, namely, a market order that hits the trading crowd on the other side, a patient limit order posted in front of the trading crowd on the same side, and a more aggressive limit order posted at the first level of the book on the same side. This means that if, for example, a seller arrives, at t_2 the book may open either empty, or with one share on A_2 or a_5, or with one share on A_1 or a_2 on the LM (SM). To economize on space, in the text we discuss the two most interesting cases, i.e., with an empty book, and with liquidity at the top of the ask side of the market (A_1, or a_2). The case with liquidity posted in front of the trading crowd delivers results that are qualitatively similar to the case with an empty book and is omitted for brevity. So for the illiquid case we compare the states of the book (in the LM and the SM) that result from an equilibrium market order submission at t_1. For the liquid case we consider the equilibrium states of the book that result from a limit order posted on the first level of the book at t_1 and that results in a state of the book with 1 share on A_1 in the LM and 1 share on a_2 in the SM. Note that only one trader arrives at each trading round so that at t_2 the book may have some liquidity only on one side of the market, the other side remaining empty.

Tesi di dottorato "Essays in Empirical Finance"
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Another benefit is that this period is the least affected by the fact that the game ends at t_4. Clearly, the "end of the game effect" is a deterrent to the provision of liquidity.[11]

The following Proposition summarizes the effects of a change in the tick size on traders' strategies, market quality and welfare at the end of period t_2. The Proposition reports results for both a large and a small change in the absolute value of the tick size .

Proposition 1 *When all else equal following a reduction in the absolute value of the tick size the number of price levels on the new price grid increases, changes in traders' order submission strategies, market quality and welfare depend on the initial state of the book.*

- *When the book opens with one share at the best possible ask (or bid), liquidity provision increases and total volume decreases; spread and aggregate depth improve and, as a result, welfare improves; depth at the best bid-offer deteriorates.*

- *When the book opens empty, liquidity provision decreases, total volume increases; spread and depth -both aggregate and at the best bid-offer- worsen and hence welfare deteriorates.*

[**Insert Table 3 and 4 and Figure 2**]

To evaluate the effects of an absolute tick size reduction, we start from a liquid book that opens at t_2 with 1 share on A_1 in the LM and 1 share on a_2 in the SM. Tables 3 and 4 show the equilibrium order submission strategies and the resulting indicators of market quality and welfare for the LM and the SM respectively.

[11] Because the game ends at the end of t_4, traders at t_4 do not use limit orders; at t_3 the incentive to post limit orders is positive and at t_2 it is even higher as even limit orders posted behind orders standing on the top of the queue have a positive execution probability.

Tesi di dottorato "Essays in Empirical Finance"
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We use an example to discuss these results and to explain how in our model a change in the tick size affects traders' choice between market and limit orders, and hence order flows, market quality and welfare. Consider a trader coming to the market at time t_2 with his own β who observes the LM with one order standing at A_1. All else equal, the trader's valuation depends on the tick size and therefore on τ, on the price of the stock, v, and the probability of execution of the limit orders, which influence the trade-off between price opportunity costs and non-execution costs.

A trader considering selling does not in equilibrium submit a limit order at A_1: there is no point in being aggressive on price given that he would still be at the back of the queue behind the order at A_1 from period t_1. The trader's equilibrium choice is therefore between a market sell order at $B_2 = v - \frac{9}{6}\tau$ and a limit sell order at $A_2 = v + \frac{9}{6}\tau$. The trader's choice between the two orders depends on his β. Equating the two payoffs (Table 1) we obtain:

$$(B_2 - \beta v) = (A_2 - \beta v) \times p_{t_2}(A_2|_{S_{t_2}}) \tag{16}$$

Solving for β and then using (4) we obtain the following threshold for a market order at B_2 and a limit order posted at A_2:

$$\widehat{\beta}_{-1^{B_2},+1^{A_2},t_2|_{S_{t_2}}} = \frac{B_2}{v} - \frac{p^*_{t_2}(A_2|_{S_{t_2}})}{1 - p_{t_2}(A_2|_{S_{t_2}})} \frac{A_2 - B_2}{v} \tag{17}$$

The trader will therefore opt for a market orders at B_2 if his personal β is lower than $\widehat{\beta}_{-1^{B_2},+1^{A_2},t_2|_{S_{t_2}}}$, and he will opt for a limit order posted at A_2 if his personal beta is in the right neighborhood of $\widehat{\beta}_{-1^{B_2},+1^{A_2},t_2|_{S_{t_2}}}$. Note that when $p_{t_2}(A_2|_{S_{t_2}})$ increases, $\widehat{\beta}_{-1^{B_2},+1^{A_2},t_2|_{S_{t_2}}}$ decreases and given that $\beta \sim U[0,2]$, the probability that the trader chooses a market order decreases. Rearranging terms, we can express the equilibrium condition (16) in terms of price opportunity costs

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and non-execution costs:

$$(A_2 - B_2) \times p_{t_2}(A_2|_{S_{t_2}}) = (B_2 - \beta v) \times (1 - p_{t_2}(A_2|_{S_{t_2}})) \tag{18}$$

The left hand side of this equation is the POC that the trader faces if he chooses a market sell order with immediate execution rather than a limit sell order at A_2, and that is equal to a 3τ price improvement times the probability that the limit order is executed, $3\tau \times p_{t_2}(A_2|_{S_{t_2}})$. The right hand side is the NEC that the trader faces if instead he chooses a limit sell order rather than a market sell order, and is equal to the loss he realizes if his order is not executed, i.e., the profit he would get from a market order sale, times the probability that the limit sell order is actually not executed, $[(1-\beta)v - \frac{9}{6}\tau] \times (1 - p_{t_2}(A_2|_{S_{t_2}}))$.[12]

Based on the definitions of POC and NEC and equilibrium conditions, it follows that when POC is smaller than NEC, a market order is preferred to a limit order and vice versa. As Table 3 shows, when the book opens with 1 share on A_1, traders on the sell side are more inclined to choose market sell orders (0.394) than limit sell orders at A_2 (0.063). By choosing a market sell order they give up a 3τ price improvement, but a limit sell order posted at A_2, behind A_1, has a low execution probability, $p_{t_2}(A_2|_{S_{t_2}})$. A lower execution probability increases the value of $\widehat{\beta}_{-1^{B_2},+1^{A_2},t_2|_{S_{t_2}}}$ and therefore increases the probability that the trader will choose a market order. This explains why in the LM traders tend to submit few limit orders at A_2. On the buy side traders' strategies are more evenly distributed -

[12] A trader considering buying chooses between a market buy order hitting A_1 and a limit buy order posted on B_2 thus entailing a 2τ price improvement (compared to the market order's execution price) and a $p_{t_2}(B_2|_{S_{t_2}})$ execution probability. Note that a buyer will not in equilibrium choose to submit a limit buy order at B_1. The reason is that the buyer is better off buying at $B_2 < B_1$ should a market order arrive at t_3. The POC of choosing a market buy order hitting A_1 are equal to the price improvement for not choosing a limit buy order posted at B_2, times the execution probability of the limit order, $(A_1 - B_2) \times p_{t_2}(B_2|_{S_{t_2}}) = 2\tau \times p_{t_2}(B_2|_{S_{t_2}})$. Analogously, the NEC of choosing a limit buy order are equal to $(\beta v - A_1) \times (1 - p_{t_2}(B_2|_{S_{t_2}})) = [(\beta - 1)v - \frac{3}{6}\tau] \times (1 - p_{t_2}(B_2|_{S_{t_2}}))$.

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they tend to choose market orders (0.306) to take advantage of the liquidity posted at A_1 or they submit limit orders at B_2 (0.237) thus getting a high execution price with a high execution probability. Note that traders know that the execution probability of a limit order posted at B_2 is high for two reasons: first, the limit order is at the top of the queue, and, second, they anticipate that the next period incoming sellers will place market rather than limit orders due to the liquidity already standing on the book at A_1.

Next consider how traders' equilibrium strategies change when the book opens with 1 share on the same level of the book ($A_1 = a_2$) but with a smaller tick size as in the SM. Table 4 shows that liquidity supply increases on the ask side as incoming sellers have an incentive to undercut the existing liquidity and place aggressive limit sell orders at a_1. In this case POC and NEC are respectively equal to $(a_1 - B_2) \times p_{t_2}(a_1|_{S_{t_2}}) = \frac{5}{6}\tau \times p_{t_2}(a_1|_{S_{t_2}})$ and $(B_2 - \beta v) \times (1 - p_{t_2}(a_1|_{S_{t_2}})) = [(1-\beta)v - \frac{9}{6}\tau] \times (1 - p_{t_2}(a_1|_{S_{t_2}}))$. The execution probability of a limit order posted at a more aggressive price level a_1 is higher than that of a limit order posted at A_2, as incoming market buyers will prefer the lower price. A higher execution probability of the limit order results in lower NEC and higher POC for LOa_1 and this explains why in equilibrium under the SM regime traders use LOa_1 more extensively than they used LOA_2 under the LM regime.[13] Hence, when the book opens liquid on the ask side and with a smaller tick size as in the SM, liquidity supply increases on the ask side as incoming sellers have an incentive to undercut the existing liquidity and place aggressive limit sell orders at a_1. On the opposite side of the book instead liquidity supply decreases for two reasons. First, there is no liquidity at b_2 ($= B_1$) and therefore no incentive to undercut orders standing on

[13] By comparing POC and NEC for LOA_2 in the LM and LOa_1 in the SM, we notice that, all else equal, NEC decreases moving from LOA_2 to LOa_1 thus explaining the greater incentive to use LOa_1. As for POC, our model shows that the gain from an increase in the execution probability outweighs the loss from a reduction in the price improvement that a limit order posted at a_1 entails compared to a limit order posted at A_2 (see Appendix).

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the book; second, traders posting limit orders away from the best bid are afraid of being undercut and therefore either post limit orders at b_5 ($= B_2$) less intensively (0.189) than in the LM at B_2 (0.237), or opt for market orders that hit the existing liquidity on a_2 (0.340).

Figure 2 shows the resulting variation in market quality and welfare moving from the LM to the SM. The effect of the "liquid book" on the ask side in so strong as to counterbalance the negative effect on the liquidity supply of the "empty book" on the bid side, so that aggregate depth increases. Inside depth initiated by sellers also increases but the effect of the bid side prevails and overall inside depth decreases. The increased limit order aggressiveness on the ask side and the reduced liquidity demand that preserves depth result in a narrower spread and in an increase in welfare.

We now move to the case of illiquid books that we proxy for by considering a book with no depth on the first price level at the beginning of period t_2 (Tables 3 and 4 and Figure 2). A trader coming to the LM and facing no depth on the first price level, will choose one of the following three equilibrium strategies on the sell side: a market sell order hitting B_2, a limit sell order at A_1 and a more patient limit sell order at A_2. Because the book is empty on first level on both sides, the equilibrium order submission strategies are symmetric. When instead the trader comes to the SM market with a smaller tick size, the trader is less inclined to post limit orders because he is afraid of being undercut. In equilibrium he will either opt for a market order hitting the trading crowd at a_5 or b_5, or if he is patient he will post a limit order at a_5 (b_5) -analogous to LOA_2 (LOB_2) for the LM-, or a more aggressive limit order at the new top of the book (a_1 or b_1). This time, however, only a few traders post aggressive limit orders because the finer price grid that the smaller tick size entails does not generate any additional advantage for aggressive limit orders as there are no orders standing on the top

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of the book which can be undercut. Therefore when the book is illiquid traders switch from limit to market orders: both the reduced liquidity supply and the enhanced liquidity demand contribute to lower market quality in terms of smaller depth and wider spread.

2.5 Relative Tick Size

Having assessed the effects of a change in the absolute tick size, we use our model to discuss the effects of a change in the relative tick size, i.e., the tick size relative to the stock price. O'Hara, Saar and Zhong (2014) maintain that the relative tick size is the most relevant measure from an economic perspective and their recent work investigates the effects of different relative tick sizes on the market quality for the NYSE stocks by exploiting the fact that in the U.S. all stocks priced above \$1 have the same absolute tick size. They find that when the stock price is higher, i.e., the relative tick size is smaller, depth at the BBO decreases but spread does not change significantly. Our model allows us to offer a theoretical support to this empirical investigation and to compare the effects of a relative tick size reduction to those of the absolute tick size.

In this section we compare changes in the absolute tick size to changes in the price of the asset that generate the same variation in the relative tick size and investigate whether the effects on market quality and welfare differ or not. To address this issue we extend our model to study how market quality and welfare change following a price increase; we then compare these changes to those obtained in the previous section following an analogous reduction in the tick size. Clearly we now assume that the price change is unexpected and as before we compare the results at t_2 conditional on different opening states of the book.[14] Table 2 shows

[14] To compare our new results with the previous ones we consider equilibrium strategies, market quality and welfare at t_2. Recall that the opening states of the book at t_2 do not change the

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the price grids for the two market structures considered: the original LM with $v = 1$ and $\tau_{LM} = 0.1$; and the two new frameworks with $v = 3$ and $\tau_{LM} = 0.1$, and $v = 3$ and $\tau_{SM} = \frac{0.1}{3}$, respectively. Note that when the asset value increases to $v = 3$ the difference between the highest ask and the lowest bid (PI) must be set proportional to the new asset value.

We now solve the model under the new specifications and obtain the results summarized in the following Proposition.

Proposition 2 *When we compare an increase in the asset price with a reduction in the absolute tick size that generates the same change in the relative tick size, we find the same effects on market quality and welfare, with the exception of quoted spread which increases.*

Our previous analysis investigates the effects of both a reduction in the absolute value of the tick size when $v = 1$. When the tick size is reduced from 0.1 to $\frac{0.1}{3}$, the relative tick size is also decreased from 0.1 to $\frac{0.1}{3}$. So if we hold the absolute value of the tick size constant to 0.1 and let the stock price increase to $v = 3$, we are able to assess the effects of an analogous reduction in the relative tick size, this time induced by an increase in the stock price rather than by a reduction in the absolute tick size.

Table 4 reports the results. Considering our previous example, and comparing the equilibrium order submission strategies in a framework with $v = 1$ (Table 3) to, all else equal, a framework with $v = 3$ (Tables 4), we observe that the changes in traders' strategies are the same and so are changes in market quality and welfare. Clearly, the only indicator of market quality that differs is quoted spread, the reason being that with $v = 3$ traders post the same orders to a price grid which is 3 times wider. We can therefore conclude that the equivalence of an absolute

tick size reduction being expected or unexpected.

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tick size reduction and a proportional increase in the asset price holds. This result is interesting as it allows us to draw clear cut predictions for the empirical works that proxy a tick size change by an asset price change.

2.6 Empirical Predictions and Analysis

Our model generates several testable empirical predictions for the effects on market quality of changes in both the absolute tick size and the relative tick size. A change in relative tick size can be achieved either by changing the absolute tick size holding the price fixed, or by changing the price and holding the tick size fixed (what we refer to as a change in price). The latter theoretical experiment matches a setting where a researcher wishes to compare stocks with different prices in a market with a uniform tick size, or when a researcher wishes to study the effect on market quality of a stock split.

> Prediction 1 When the absolute tick size reduction is large enough to generate new levels on the price grid, quoted spread widens, aggregate and BBO depth decreases and volume increases if the book is illiquid, while quoted spread narrows, aggregate depth increases, BBO depth and volume decrease if the book is liquid.

We test Prediction 1 below. First, however, we want to emphasize that our model generates an additional empirically testable prediction.

> Prediction 2 A change in the relative tick size due to an increase in the stock price has the same effects on market quality and welfare as a change in the relative tick size due to a reduction in the absolute tick size. All else equal, when the price increases, quoted spread increases, BBO depth decreases and the effects on aggregate depth, rela-

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tive spread and volume depend on the liquidity of the book (as for the tick size change).

The equivalence result in Prediciton 2 can be empirically tested by considering asset price changes that perfectly match absolute tick size changes on any tick size grid. We leave the empirical testing of Prediction 2 for future research.

2.6.1 Regression Discontinuity Design: LSE

To test the model's predictions on the effect of a reduction in the tick size on market quality we exploit the price format schedule on the London Stock Exchange (LSE). The London Stock Exchange's flagship electronic order book is named SETS and it trades FTSE100, FTSE250, FTSE Small Cap Index constituents, Exchange Traded Funds, Exchange Trading Products as well as other liquid AIM, Irish and London Standard listed securities. SETS is one of the most liquid electronic order books in Europe. Listed stocks are grouped into segments; each segment is characterized by its own price format schedule. The price format schedule specifies the minimum tick size for each price level. Therefore, when the price of a stock crosses a specified threshold, the tick size changes immediately and the new tick size stays in effect until the stock price again crosses the threshold.[15]

This setting lends itself very naturally to a regression discontinuity design (RDD). According to Cameron and Trivedi (2005), a RDD is a quasi-experimental design in which the probability of receiving a treatment is a discontinuous function of one or more underlying variables. Such a design can arise in circumstances where a treatment is triggered by an administrative or organizational rule. The intuition behind a RDD is that observations below and above the cutoff can be compared

[15] For further reference, see The LSE Millennium Guide to the Trading System at this link https://dl.dropboxusercontent.com/u/7214702/millennium-exchange-business-parameters.xls and the Millennium Exchange Business Parameters document at this link https://dl.dropboxusercontent.com/u/7214702/Guide%20to%20the%20LSE%20Trading%20System.pdf.

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directly to draw inference on the effect of the treatment. The design is valid if the stock's price can be considered as good as randomly assigned below or above the threshold.

As we are dealing with the case of treatment assignment which is public knowledge (i.e., the dynamic price grid), the limit orders (or the trades) could in principle try to manipulate the assignment variable by crowding on one side of the cutoff. If it is the case that the assignment variable has been manipulated, the RDD is not valid. To verify that the RDD is valid in our application, we run the density discontinuity test presented by McCrary (2008) to examine whether or not the density is continuous at the thresholds. We run the test for the continuity for each of our thresholds and we do so both for all stocks trading around a threshold using intradaily data and for four portfolios of stocks trading in the price-bands defined by the thresholds using daily closing prices only. The latter test reduces the chance that we pick up a significant effect at a threshold simply because we have a large number of observations. We do not find any evidence of discontinuity at the thresholds.[16] Therefore, we conclude that the RDD is valid and use this methodology to analyze the effect on depth, quoted and relative spreads and volume when the stock price crosses the threshold.

Our data is taken from the Thomson Reuters Tick History Database[17] and our sample period spans from January 2013 to December 2013. We select stocks for which price crosses one of the existing thresholds at least one time during the sample period and we end up with a sample of 142 stocks: 20 that cross the 10 GBX threshold, 21 that cross the 100 GBX threshold, 60 that cross the 500

[16] The results of the density discontinuity and placebo tests are available on the Online Appendix at the following link: https://dl.dropboxusercontent.com/u/7214702/BCRWW_OnlineAppendix.pdf

[17] We acknowledge SIRCA for providing the access to the Thompson Reuters Tick History Database.

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GBX threshold and 41 that cross the 1000 GBX threshold.[18] Table 5 Panel A provides descriptive statistics for each group sorted by the thresholds, along with their minimum tick size change. As Table 5 shows, the tick size doubles as price passes the 10, 100, and 1000 GBX thresholds from below, while it increases by a factor of 5 as the stock price passes the 500 GBX threshold.[19]

Table 5A also shows the depth and quoted spread increase on average when a stock crosses a threshold from below for all subsamples. Relative spread and volume increase on average for two subsamples (1,000 GBX and 500GBX) but either do not change or decrease for the remaining two subsamples. Finally, note that the average size of LSE sample firms range from 1.8B GBP which is just above the cutoff of $2.5B for Large Cap U.S. stocks ($2.5B-$50B) to 100M GBP which would be classified as Micro Cap U.S. stocks ($100M - $300M) depending on the sub-sample. Mackintosh (2014) finds that more than one-fourth of all U.S. Large Cap stocks and more than nine out of ten Mid, Small and Micro Cap securities will be affected by the proposed SEC Tick Size Pilot which increases the minimum tick size to 5 cents. In other words, while the LSE sample consists of mostly large stocks, it is representative of many stocks that will experience a tick size increase under the proposed SEC Tick Size pilot.

Our data on prices (executions, bid and ask) and volume is reported for 10 minute intervals. To calculate depth, we first calculate the BBO and take a snapshot of the BBO depth at the beginning of each 10 minute during the trading day. We then merge this new data series on depth with the other data sources.

We first study the effect of the change in the tick size on market quality (i.e., BBO depth and quoted absolute and relative spread). We estimate the following panel regression:

[18] The acronym GBX stands for pence sterling (1 GBP/100). Stocks on the LSE are traded in pence.

[19] For these segments the dynamic tick schedule is in place: the tick size in operation is determined with reference to the intended price of the incoming order/quote.

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$$y_{i,t} = b_i + b_1 D_{i,t} + b_2(price_{i,t} - c) + b_3(price_{i,t} - c)D_{i,t} + \varepsilon_{i,t} \quad (19)$$

where $price_{i,t}$ is the price, which is reduced by c to locate the threshold at zero, where c can be either 10, 100, 500 or 1000, depending on the group we are considering. $D_{i,t}$ is an indicator that takes the value of 1 if $price_{i,t}$ is equal to or greater than c and a value of 0 if $price_{i,t}$ is less than c. $D_{i,t}$ generates a discontinuity in the treatment around the threshold which allows for the estimation of the effect of the treatment. The index i is for stock and the index t is for time. We include all the observations which satisfy the following condition: $-h \leq price_{i,t} - c \leq h$, where h is the bandwidth. We select three different bandwidths equal to 1%, 2% and 3% of the thresholds.

We estimate a locally linear panel regression with fixed effects and standard errors clustered by stock to obtain our estimated dummy coefficients.[20] We present the results for BBO depth, quoted spread, relative spread and volume as outcome variable (y) and the stock price as assignment variable. To economize on space we report the results for the 500 GBX group using a bandwidth of 1% in Table 6 and summarize results for the sign and significance of the $D_{i,t}$ coefficient for the others group of stocks and for the other bandwidths (2% and 3%) in Table 7.[21] We conduct extensive robustness tests by varying the bandwidth and find qualitatively similar results.[22]

[**Insert Tables 5, 6 and 7 here**]

Tables 6 and 7 show that an increase in the tick size is associated with an increase both in depth and quoted and relative spreads. Moreover, the coefficients

[20] We use locally linear regressions in favor of the alternative local nonparametric methods. Locally linear methods have been shown to have attractive bias properties in estimating regression functions at the boundary (Fan and Gijbels, 1992), and enjoy rate optimality (Porter, 2003).

[21] All the results from the regressions are reported in the Online Appendix.

[22] Results are available from the authors upon request.

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of the dummy variable $D_{i,t}$ are statistically significant. To gauge the economic significance of the variables, we compare the estimated coefficients to the sample average below 500 GBX (Table 5 Panel A). Keep in mind that the estimation uses stock and time dummies, hence the estimated coefficients are not exactly the differences in the means for the subsamples in Table 5. Depth increases by 1,311 shares, which means that quoted depth increases by roughly 75% (1,311/1,750) when the price goes from just below 500 GBX to above 500 GBX. This change in depth is highly economically significant. Similarly, the increase in quoted spread is 0.4861 GBX which is economically significant and larger than the increase in tick size from 0.1 to 0.5 GBX. We report the results in a summary fashion for the additional subsamples (10 GBX, 100 GBX, and 1000 GBX) in Table 7. The relative spread increases by 10 basis points which is sizable relative to the average relative spread of 48 basis points. Finally, our estimated coefficient shows that volume declines by -10,632 shares when the price goes from below 500 GBX to above 500 GBX. This is more than a 50% decline compared to the average volume of 21,046 shares. Note, however, that the estimated coefficient for volume is the one that is most affected by the cross-sectional heterogeneity (which we do not control for when computing the averages in Table 5 Panel A, but do control for in the RDD).

Taken together, the results for spreads and BBO depth are consistent with the predictions of our theoretical model for liquid stocks, i.e., a substantial reduction (increase) in the absolute value of the tick size decreases (increases) both spread and BBO depth. By contrast, the observed significant decline in volume for the 500GBX and the 1000 GBX subsamples are not consistent with our model's predictions. However, note that the results for volume are generally weaker and the dummy is not significant for the 10 GBX and 100 GBX subsamples. Our volume measure includes only share volume reported on the LSE. Therefore, we believe

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that the reason for this decline in volume is that order flow migrates away from the lit markets, which in the U.K. all have the same pricing grid and thresholds, to the dark markets such as Turquoise Dark which has a smaller tick size as it provides midquote execution when the tick size increases.

We conduct extensive robustness tests to further validate our results. First, we vary the bandwidths beyond the three reported in Table 7 and .nd that the results are in each case qualitatively unchanged. We then calculate the optimal bandwidth using the algorithm suggested by Imbens and Kalyanarama (2012) and use the optimal bandwidth (which in all cases are in the range of 2-3%) and find the results to be qualitatively unchanged. Finally, we conduct placebo tests by re-running the RDD based on how prices move across fictitious thresholds in the neighborhood of the true thresholds for the group of 500 GBX. In no case do we find significant changes in market quality measures for the fictitious thresholds.

2.6.2 Regression Discontinuity Design: Nasdaq

In this section we exploit a feature of Rule 612 of Regulation NMS which states that in the U.S. the tick size changes from \$0.01 to \$0.0001 for stocks priced less than \$1. As a result of Rule 612, The U.S. stocks crossing the \$1.00 threshold from below experience hundred-fold tick size increase. Such a large tick size variation should affect market quality significantly according to our model's predictions, and we therefore examine whether the empirical evidence is consistent with our model's predictions for an absolute tick size change.

To run the RDD we select a sample of all Nasdaq listed stocks whose closing price at September 30, 2010 was between \$0.80 and \$1.20. We select Nasdaq because the vast majority of listed low priced stock trade on Nasdaq. We further restrict our sample by retaining only the stocks whose price crosses the \$1.00 threshold at least once during the sample period. These filters reduce the sample

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to 20 stocks, but note that a particular stock crosses the threshold many times during the year. Table 5B reports the summary statistics for the Nasdaq sample. Average bid-depth, quoted spread relative spread, and volume all increase in the univariate analysis, but we want to make sure to control for stock fixed effects which we do in the RDD below. Note also that the average firm in this sample has a market capitalization of $45.6M which puts it squarely in the Nano cap segment (below $100M) for which two-thirds of all listed stocks are going to be affected by the SEC Tick Size Pilot.

As was the case for the LSE sample, identification of the treatment effect relies on stocks which cross the threshold (Lee and Lemieux (2010)) and we therefore need this additional restriction. The treatment assignment is again public knowledge (i.e., Rule 612 of Reg NMS) and, as for the LSE experiment, we do not find any evidence of manipulation based on examining the sample density for discountinuity around the threshold (McCrary, 2008).

We study the effect of the tick size change on market quality (i.e., log of bid depth, quote and relative spread and consolidated volume). To build our dataset, for each stock and day we take a snapshot of the market-wide BBO every hour starting from 9:30:00 AM. As before, we estimate the RDD using locally linear panel regression with fixed effects and clustered standard errors by stock. For the U.S. sample we set c=1.00 as there is only one threshold at $1.00.

We include all the observations which satisfy the following condition:$-h \leq price_{i,t} - c \leq h$, where h is the bandwidth that we select equal to 10%, 15%, and 7.5% of $1.00. We replicate the analysis also using the optimal bandwidth using the algorithm suggested by Imbens and Kalyanaraman (2012) and the results are qualitatively unchanged. The results of the estimation are in Table 8.

[**Insert Table 8 Panel A here**]

The coefficients on the dummy variable $D_{i,t}$ show that for both bid depth,

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quoted spread and relative spread the discontinuity is statistically significant. Bid depth, quoted spread and relative spread all increase significantly moving from below to above the \$1 cutoff. The bid-depth increases by between 1.46 and 1.57 log(shares) depending on the bandwidth which is economically large relative to the average depth when the stock price is below \$1 of 6.71 log(shares).[23] Similarly, the quoted spread increases by between 1.3 and 1.4 cents and the relative spread increases by between 1.5 and 2.7 percentage point depending on the bandwidth. Again, these numbers are economically significant relative to the averages for the sub-sample when the price is below \$1.00 of 99 cents quoted spread and 1.2 percent relative spread respectively. Therefore, the results are consistent with the predictions for an absolute tick size increase for liquidity stocks: the inside spread deteriorates and bid depth improves.

We examine the effects of the change in the tick size on consolidated volume based on our RDD in the last column of each panel in Table 8. The coefficient on the dummy variable $D_{i,t}$ is positive as predicted by our model. However, the coefficient on the dummy variable is not statistically significant at conventional levels.[24]

As can be seen in Table 8, our Nasdaq RDD results are robust to using a 15% and 7.5% bandwidth. The results are also qualitatively unchanged if we use the optimal bandwidth based on the algorithm suggested by Imbens and Kalyanarama (2012). We repeat the analysis using the ask price as assignment variable to determine whether the stock price is above or below \$1.00 instead of the bid price.

[23] The estimates imply that volume goes from 821 share to 3,535 to 3,946 shares depending on bandwidth.

[24] We explore this result further and separate TAQ reported consolidated volume into Dark (EX=D in TAQ) and Lit (EX ne D in TAQ) and find that there is a marginally significant increase in lit volume but no significant change in dark volume at the threshold. If we look at Dark and Lit volume as a percentage of consolidated volume, we find that %Dark decreases significantly and %Lit increases significantly at the threshold. Note that our measure of Dark includes internalized trades, which most likely accounts for the difference between our volume results and those found by Kwan, Masulis, and McInish (2015).

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In this case the bid depth is substituted by the ask depth for consistency. The results remain qualitatively unchanged. Note that the conclusion of the RDD is valid only in the neighborhood of the cutoff and cannot be generalized to all stocks.

2.6.3 Variation in Relative Tick Size

In this Section we complement the evidence with tests of the effects of the relative tick size on quoted and relative spread, and BBO depth by looking at a cross-section of Nasdaq and NYSE stocks. This sample has the additional advantage of being drawn from the same stock market as most prior studies of the effects of tick size on market quality.

Note that in this case, we test whether differences in the relative tick size in the cross-section influences market quality. Note also that the tick size for U.S. stocks priced above \$1.00 is \$0.01. Hence, the variation in relative tick size derives exclusively from cross-sectional variation in the stock price.

Our model shows that a change in the absolute tick size and a change in the stock price should produce the same effects on market quality , with the exception of quoted spread that should increase proportionally to the stock price. So we can consider the effect of a change in the stock price as a proxy for a change in the tick size. Our model predicts that a reduction in relative tick size due to an increase in the stock price should produce a reduction in BBO depth and an increase in quoted spread. However, the predictions for the effects of a change in price on the relative spread and volume depend on the liquidity of the book. When the book is liquid, the model predicts that both relative spread and volume should decrease following a reduction in the relative tick size, the opposite holding when the book is illiquid.

We construct a sample of stocks stratified by price and market capitalization for both Nasdaq and NYSE. As of December 31, 2009 we identify all common

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stocks in CRSP which are NYSE or Nasdaq listed. Then we divide all NYSE listed common stocks (i.e., share code 10 or 11), into terciles by market capitalization and price and form nine mutually exclusive groups. From each group we randomly draw 10 stocks for a total of 90 NYSE stocks. We repeat the procedure for Nasdaq stocks using the NYSE breakpoints. This way we create groups of stocks which are comparable across exchanges by market capitalization and price. Our final sample includes 180 stocks and spans from October 1 to November 30, 3010, for a total of 42 trading days. Descriptive statistics for this sample are reported in Table 5C. Note that the average market capitalization of stocks in this sample is \$7.3B. However, by design one-third of the stocks in the sample have market capitalization below \$869M, and the average market capitalization of firms in the first tercile is \$485M. Hence, there is significant overlap also between this sample and stocks that are going to be affected by the SEC Tick Size Pilot.

To test how the relative tick size affects market quality we run daily Fama-MacBeth regressions of measures of market quality on stock price sampled at the close. In the regressions we control for other stock characteristics that have been shown to affect market quality such as share volume, depth (time-weighted BBO depth), quoted spread in cents, order imbalance (buy imbalance relative to volume), and volatility (high-low/high).

[**Insert Table 9 here**]

Table 9 shows that for the full sample of NYSE and Nasdaq stocks (first column) when the closing price increases, i.e., the relative tick size decreases, BBO depth decreases significantly and both quoted and relative spreads increase significantly. To gauge the economic significance of the estimated coefficient on the closing price, consider an increase in price from \$25 to \$35 (the sample average is \$29.70). This experiment corresponds to a reduction in the relative tick size by a

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factor of 1/10. A $10 change in price is associated with a decrease in log(bid-depth) of -0.33 which is economically significant relative to the average log (bid-depth) of 6.73 as it implies a reduction of the bid-depth from the sample average of 837 shares (Table 5 Panel C) to 602 shares, a difference of 235 shares. The changes in quoted spreads are also economically significant. The quoted spread increases by 1.9 cents for a $10 change in price or 48% compared to the sample mean of 3.96 cents (Table 5 Panel C). By contrast, the relative spread increases by 0.33 basis points when the price changes by $10 compared to the sample mean of 15 basis points, which is economically insignificant. The effects of the other control variables are also statistically significant, and with the predicted signs. Specifically, stocks with higher share volume have lower quoted spreads and higher depth, and stocks with higher relative order imbalance and higher volatility have wider quoted absolute and lower BBO depth.

Table 9 shows that for the full sample of NYSE and Nasdaq stocks when the closing price increases, i.e., the relative tick size decreases, consolidated volume increases significantly which is the opposite of what we would predict would happen for liquid books. To gauge the economic significance of the estimated coefficient on the closing price, again consider an increase in price from $25 to $35 which corresponds to a reduction in the relative tick size by a factor of 1/10. A change of $10 in closing price would be associated with an increase in log(volume) of 0.31, which translates to an increase in share volume from an average of 5,923,018 shares to 8,075,591 shares (Table 5 Panel C). In other words, the positive effect on volume of a decrease in the relative tick size is economically large. The fact that volume increases following a tick size reduction suggests that the population of traders changes following a tick size reduction. Specifically, we conjecture that this result is related to additional traders being drawn to the market when the relative tick

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size declines. We defer a discussion of this conjecture to the conclusions.[25]

In related work, O'Hara, Saar and Zhong (2014) study the relation between relative tick sizes on market quality focusing specifically on the role of HFT market making strategies. They use a matched sample methodology and examine whether the central moments of the distributions of measures of market quality differ significantly across groups of stocks sorted by stock price. Like us, these authors find that a higher stock price, i.e., a lower relative tick size, is associated with a higher quoted spread and more total depth but their results for depth at the BBO are weaker than ours. Interestingly they do not find significant results for relative spread. Based on the RDD around the different LSE thresholds and the $1 U.S. threshold, we find that the relative spread decreases following a reduction in tick size. On the contrary, our Fama Mac Beth regressions of relative tick size on the closing price show a positive relation. We attribute the difference in our results to the fact that when we consider the LSE sample with a clean tick size grid we are able to control for other factors that have been shown to affect quoted and relative spreads when examining the effect of the relative tick size on market quality.

2.7 Conclusions

Motivated by the recent JOBS Act (2012), we set out to study the relationship between the tick size and market quality and trader welfare respectively. Given that the objectives of the JOBS Act are to enhance capital raising and secondary market liquidity for Emerging Growth Companies (EGCs), we were especially interested in finding out if a different (larger) tick size could be theoretically mo-

[25] To show that these results are robust, we re-run the Fama-MacBeth regressions for each of the subsamples by size and by price and the results do not change qualitatively (Internet Appendix). We also vary the control variables by excluding depth in the spread and volume regressions and by excluding spread in the depth regression. Also in this case the results remain qualitatively unchanged.

Tesi di dottorato "Essays in Empirical Finance"
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tivated for stocks that are less liquid in that their order books are thinner and spreads wider.

We develop a model of a multi-period Public Limit order Book (PLB) where liquidity builds endogenously as rational traders with private valuations determine whether to supply or demand liquidity, or refrain from trading, based on the available orders in the PLB. We use this rich setting to evaluate the effects of a change in the tick size on market quality and welfare. We consider two experiments: a change in the absolute tick size holding the price of the stock fixed; and a change in the price of the stock, holding the absolute tick size fixed. The first experiment generates empirical predictions about the effects of a change in the absolute tick size on market quality and welfare for a particular stock. The latter experiment generates predictions about market quality and welfare for stocks that trade with the same tick size but at different price levels. This experiment also generates predictions about a related topic: the effects of a stock split on market quality and welfare.

Our model shows that the effects of an absolute tick size change depend on the liquidity of the book. Market quality improves when the tick size falls for liquid books; whereas for illiquid books it deteriorates. When the tick size falls sufficiently for more price levels to become available within the quoted spread in a book with an initial limit order queue, some traders switch from market to limit orders, attempting to undercut the resting orders on the book. As a result, the quoted spread for liquid books narrows and total depth increases (although inside depth declines). This switch from market to limit orders causes trading volume for liquid books to decline following a tick size reduction. However, a sufficient number of trades take place at narrower spreads for trader welfare in liquid books to increase. By contrast, the quoted spread for illiquid books widens and both total and inside depth declines. When there is no liquidity in the initial book,

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di CONSONNI FRANCESCO
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some traders switch from limit to market orders. The reason is that the execution probability of limit orders [on the original price grid] falls because of the possibility of undercutting. The change from limit to market orders causes volume to increase, but since the trades take place at worse prices traders' welfare declines.

Under the assumption that we can interpret our setting of an illiquid book as a reasonable characterization of less liquid stocks or EGCs in the language of the JOBS Act (2012), our theoretical model suggests that it may indeed have been harmful to reduce the tick size to one penny for these stocks. Specifically, the model suggests that a tick size reduction for illiquid books results in a deterioration of market quality (wider spreads and lower depth) and lower welfare. However, note that the model also predicts that the lower tick size following decimalization should have been associated with higher trading volume for EGCs.

We also find that a change in the absolute tick size holding price constant and a change in the price that results in the same change in the tick to price ratio are equivalent. In other words, the effects of changing price on market quality and welfare are identical to those described above with the important caveat that the quoted spread will be different. Specifically, if the stock price doubles the absolute quoted spread will be twice as large as the absolute quoted spread would be after the tick size is cut in half. Similarly, after a two-for-one stock split the model predicts that the absolute quoted spread will be half as large as it would be after a doubling of the tick size. This equivalence holds both for large and small changes in the absolute tick size and price respectively.

Our model highlights that when setting the tick size regulators and exchanges face a fundamental trade-off between the effects on market quality and welfare and the effects on volume. More precisely, we find that welfare tends to be inversely related to the quoted spread but not necessarily positively related to depth. For liquid books a substantial reduction in the tick size improves spreads and welfare,

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but this comes at the price of reduced trading volume. Similarly, a substantial reduction in the tick size for illiquid books deteriorates spreads and welfare, but is associated with an increase in trading volume. The reason for this trade-off is that traders in our model optimally choose whether use market or limit orders, and at which prices to post limit orders. When traders switch from market to limit orders, fewer trades take place. Conversely, when traders switch from limit to market orders, more trades occur. This is a fundamental insight that highlights the importance of building models where liquidity arises endogenously through optimal order submission strategies adopted by rational traders.

We test our model's predictions for market quality and volume based on both European and U.S. liquid stocks. We explore both time-series variation in the absolute tick size for individual stocks and cross-sectional variation in the relative tick size. We use a regression discontinuity design (RDD) to study stocks from both the LSE and Nasdaq for which prices transition across thresholds which are associated with a large tick size change. We also study a large cross-section of stocks from both Nasdaq and NYSE for which the tick size is fixed at \$0.01 but there is considerable variation in the stock price. For the cross-sectional analysis we use daily Fama-MacBeth regressions. Our empirical analyses generally support our theoretical hypotheses regarding the effects of a tick size reduction on market quality for stocks with liquid books. Specifically, we find that a lower absolute tick size is associated with lower quoted and relative spreads and lower inside depth.[26] Therefore, our empirical results are consistent with traders both on the LSE and in U.S. markets responding to a reduction in the absolute tick size by switching from market to limit orders, thereby undercutting the existing liquidity in the book.

The empirical evidence does not support our model's predictions that a lower tick size should be associated with lower volume. We find that a lower absolute

[26] As we do not have order level data, we are unfortunately unable to test the model's predictions on total depth.

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tick size is associated with higher volume for the higher price thresholds on the LSE, but there is no significant change for the lower price thresholds. Moreover, a lower relative tick size caused by a higher stock price is associated with higher volume for a large cross-section of U.S. stocks. By contrast, a lower absolute tick size for Nasdaq stocks trading around $1.00 is associated with a lower volume as predicted by our model, but the effect is not statistically significant.

We believe that the lack of empirical support for our model's predictions regarding volume suggests that the population of traders changes following a tick size reduction. Specifically, it is possible that traders, e.g., High Frequency Traders (HFTs), are drawn to the market following a (absolute or relative) tick size reduction because their trading strategies are profitable with a lower tick size. While HFTs employ a variety of strategies, two important categories of HFTS are those that specialize in market making (MM); and those that pursue more aggressive strategies and are basically liquidity demanders trading via Smart Order Routers (SORs). In general HFT market makers are more active in liquid stocks with larger tick sizes as their MM activity is more profitable with larger spreads (O'Hara, Saar, and Zhong, 2014). HFT liquidity demanders trading via SORs are instead attracted by liquid stocks with smaller tick size. Therefore, our conjecture is that the increase in volume we observe in the data is caused by more opportunistic liquidity-demanding HFT traders reaching the order book via SORs following a tick size reduction. We leave it to future research to extend the theoretical model to incorporate a fringe of traders that may be attracted to a market following a tick-size change.

Finally, our theoretical model and our empirical findings allow us to shed light on the proposed SEC Pilot that is aimed at studying the effect of increasing the tick size for a sample of less liquid stocks. The hypothesis expressed in the JOBS Act (2012) is that a larger tick size would provide market participants with better

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incentives to post limit orders or quotes, hence increase liquidity provision and especially market making activity. More market making activity would in turn increase both liquidity and analyst coverage, hence attracting more investors to the market resulting in more volume. While our model is silent on the effect of analysts' coverage, we can use our results to discuss the link between the tick size and liquidity. Specifically, we show theoretically that there is generally a trade-off between market quality and trading volume. Hence, the only way to achieve both an improvement in market quality and volume is to attract new traders to the market.

Our model and empirical results show that an increase in the tick size for a liquid book causes traders to switch from limit to market orders, resulting in a wider spread and higher inside depth. The model predicts that volume will increase following a tick size increase, but the empirical evidence shows that volume instead declines. Therefore, while some opportunistic liquidity providers such as HFT MMs may be attracted to the market due to the wider spread, the reduction in volume we observe suggests that a large fraction of opportunistic traders such as HFTs using SORs may leave the market following a tick size increase. For illiquid books, the model instead predicts that an increase in the tick size causes traders to switch from market to limit orders, resulting in narrower spreads, higher inside and total depth and lower volume. The narrow spreads discourage opportunistic HFT MMs but the question is if the narrower spreads will attract sufficient interest from opportunistic HFT using SORs to counterbalance the decline in volume? Our empirical evidence covers liquid securities, so we cannot immediately draw conclusions from these stocks about the effects on volume of a tick size increase for illiquid stocks. However, our conjecture is that the interest from HFTs using SORs would be limited as HFTs tend to favor highly liquid stocks (Brogaard, Hendershott, Hunt and Ysusi, 2014) and we therefore doubt that volume would

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increase. This is of course ultimately an empirical question that can be investigated once the SEC Pilot is implemented.

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Appendix

The following Lemma is necessary to prove Proposition 1:

Lemma 1 *For $\frac{\tau}{v} \in (0, 0.1]$, if at time $t \neq t_4$ at least one limit order strategy has positive execution probability, there will always exist a β value for which a limit order is optimally selected by the incoming trader.*

Traders' equilibrium β-thresholds, and hence strategies, crucially depend on the state of the book which affects the execution probability of limit orders. Consider the LM as an example. There are four possible scenarios: (a) there is room for limit orders on both sides of the market, i.e., $p_t^*(A_k|S_t) \neq 0$ and $p_t^*(B_k|S_t) \neq 0$ (b) the book opens full on the ask side, i.e., $p_t^*(A_k|S_t) = 0$ and $p_t^*(B_k|S_t) \neq 0$ (c) the book opens full on the bid side, i.e., $p_t^*(A_k|S_t) \neq 0$ and $p_t^*(B_k|S_t) = 0$ (d) the book is full on both sides, i.e., $p_t^*(A_k|S_t) = 0$ and $p_t^*(B_k|S_t) = 0$. The Lemma states that in scenarios (a), (b) and (c), i.e., unless the book is full on both sides, a limit order is always an equilibrium strategy on either both sides of the market, or the bid side, or the ask side, respectively. Because (b) and (c) are just a simplified version of (a), we discuss directly scenario (a) and assume without loss of generality that only one limit order strategy on each side of the market has positive execution probability. The possible available strategies are $H_t^{LM} = \{-1^{B_{k'}}, +1^{A_k}, +1^{B_k}, -1^{A_{k'}}, 0\}$, where k indicates the price level at which a lmit order is posted and and $k\prime$ indicates the price level that a market order hits, and the corresponding profits:

$$\boxed{\begin{array}{lcll} H_t^{LM} = & -1^{B_{k'}} & : & B_{k'} - \beta v \\ H_t^{LM} = & +1^{A_k} & : & (A_k - \beta v) \cdot p_t^*(A_k|S_t) \\ H_t^{LM} = & +1^{B_k} & : & (\beta v - B_k) \cdot p_t^*(B_k|S_t) \\ H_t^{LM} = & -1^{A_{k'}} & : & \beta v - A_{k'} \\ H_t^{LM} = & 0 & : & 0 \end{array}} \tag{A1}$$

The thresholds between these strategies are:

$$\begin{aligned} \beta^{LM}_{-1^{B_{k'}},+1^{A_k},t|S_{t-1}} &= \frac{B_{k'}}{v} - \frac{p_t^*(A_k|S_t)}{1-p_t^*(A_k|S_t)} \cdot \frac{A_k - B_{k'}}{v} \\ \beta^{LM}_{+1^{A_k},+1^{B_k},t|S_{t-1}} &= \frac{p_t^*(A_k|S_t)A_k + p_t^*(B_k|S_t)B_k}{p_t^*(A_k|S_t) + p_t^*(B_k|S_t)} \cdot \frac{1}{v} \\ \beta^{LM}_{+1^{B_k},-1^{A_{k'}},t|S_{t-1}} &= \frac{A_{k'}}{v} + \frac{p_t^*(B_k|S_t)}{1-p_t^*(B_k|S_t)} \cdot \frac{A_{k'} - B_k}{v} \end{aligned} \tag{A2}$$

The β-thresholds are a function of the relative tick size, $\frac{\tau}{v}$, and degenerate to 1 when $\frac{\tau}{v} \to 0$. Consider for example $\beta^{LM}_{-1^{B_{k'}},+1^{A_k},t|S_{t-1}}$, for $S_{t-1} = S_{t_2}$, $B_{k'} = B_2$ and $A_k = A_1$. We assume that at t_2 the book starts empty, hence S_{t_2} is [0000]; other example of S_{t_2}

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are [1000], and [0001].[27]

$$\beta^{LM}_{-1^{B_2},+1^{A_1},t_3|S_{t_2}} = \frac{B_2}{v} - \frac{p^*_{t_3}(A_1|S_{t_3})}{1-p^*_{t_3}(A_1|S_{t_3})} \cdot \frac{A_1-B_2}{v} = 1 - \frac{3}{2} \cdot \frac{\tau}{v} - \frac{\frac{1}{2}-\frac{\tau}{4v}}{1-(\frac{1}{2}-\frac{\tau}{4v})} \cdot \frac{2\tau}{v} = f(\frac{\tau}{v})$$

It is easy to show that $\beta^{LM}_{-1^{B_2},+1^{A_1},t_3|S_{t_2}} \to 1$ when $\frac{\tau}{v} \to 0$. To guarantee that a limit order is an equilibrium strategy provided that $p^*_t(A_k|S_t) \neq 0$ and $p^*_t(B_k|S_t) \neq 0$, we need to check that for $\frac{\tau}{v} \in (0, 0.1]$ the following inequalities hold:

$$\begin{aligned} \Delta d\beta_t(-1^{B_{k'}}, +1^{A_k}, +1^{B_k}) &= d\beta^{LM}_{-1^{B_{k'}},+1^{A_k},t|S_{t-1}}/d\tfrac{\tau}{v} - d\beta^{LM}_{+1^{A_k},+1^{B_k},t|S_{t-1}}/d\tfrac{\tau}{v} < 0 \quad (A.3) \\ \Delta d\beta_t(-1^{A_{k'}}, +1^{B_k}, +1^{A_k}) &= d\beta^{LM}_{+1^{B_k},-1^{A_{k'}},t|S_{t-1}}/d\tfrac{\tau}{v} - d\beta^{LM}_{+1^{A_k},+1^{B_k},t|S_{t-1}}/d\tfrac{\tau}{v} > 0 \end{aligned}$$

for the ask and bid side, respectively. If these two requirements are satisfied, so that $H_t = \{+1^{A_k}, +1^{B_k}\}$ are equilibrium strategies. We present graphically $\Delta d\beta_t$, and focus on the ask side, the bid side being symmetric. Figures A.1, A.2 and A.3 show the difference in the β-threshold derivatives at t_1, t_2 and t_3 respectively. For example, Figure A.2 shows that at t_2 for $\frac{\tau}{v} \in (0, 0.1]$, $\Delta d\beta_t(-1^{B_{k'}}, +1^{A_k}, +1^{B_k}) < 0$. Therefore in scenario (a) a limit sell order is always an equilibrium strategy at t_2. Similar results are obtained for t_1 and t_3, by observing Figures A.1 and A.3. The proof for the SM follows the same methodology and is omitted.

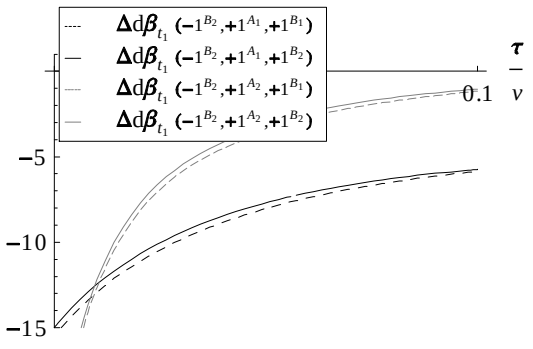


Figure A.1 - Difference in β-threshold derivatives at t_1

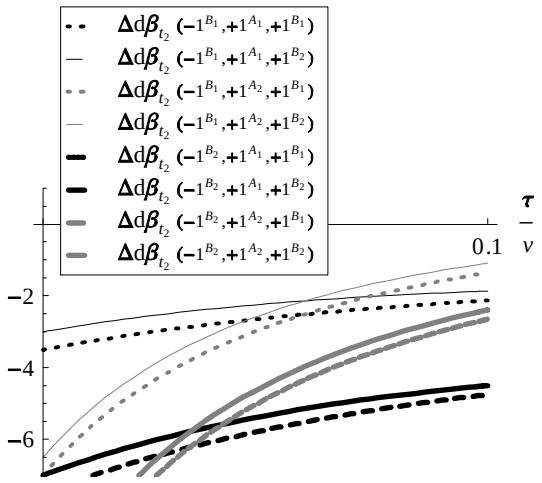


Figure A.2 - Difference in β-threshold derivatives at t_2.

[27] From here onwards, to simplify the notation, we omit commas. For example, $[0, 0, 0, 0]$ is simplified into [0000].

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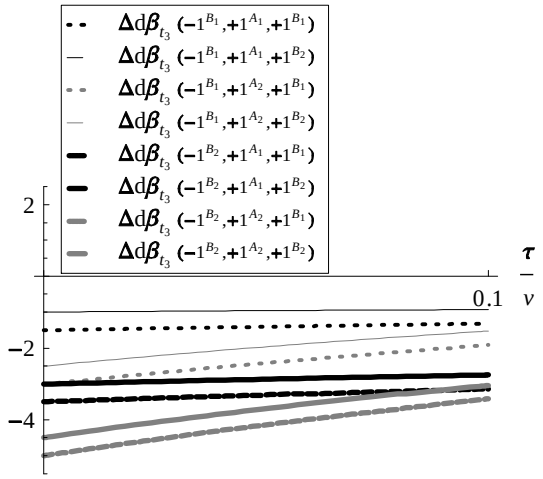


Figure A.3 - Difference in β-threshold derivatives at t_3.

A Proof of Propositions 1 and 2

In this proof we concentrate on the case of a book that opens empty at t_2. Our proof can be easily extended to the case with the book opening with one or more shares on the ask side, on the bid side or on both sides.

A.1 Large Market (LM)

At t_2 the book opens as $S_1 = [0000]$, and traders' strategy space is $\{-1^{B_2}, +1^{A_2}\}$. Each strategy corresponds to an opening book at t_3 equal to [0000], [1000], [0100], [0010], [0001], and [0000], respectively. The model is solved by backward induction. We refer to equations (3), (4) and (5) for the equilibrium strategies at t_4, and focus directly on periods t_3 and then t_2, which is the period we consider to compare the equilibrium strategies associated to a large and to a smal tick size respectively.

Period t_3. We present as an example the book that opens at t_3 with one share on A_2, i.e., $S_{t_2} = [1000]$. Traders' strategy space, $H_{t_3}^{LM}$, and the corresponding payoffs at t_3 are:

$$\begin{array}{lcll} H_{t_3}^{LM} = & -1^{B_2} & : & B_2 - \beta v \\ H_{t_3}^{LM} = & +1^{A_1} & : & (A_1 - \beta v) \cdot p_{t_3}^*(A_1|[1100]) \\ H_{t_3}^{LM} = & +1^{B_1} & : & (\beta v - B_1) \cdot p_{t_3}^*(B_1|[1010]) \\ H_{t_3}^{LM} = & +1^{B_2} & : & (\beta v - B_2) \cdot p_{t_3}^*(B_2|[1001]) \\ H_{t_3}^{LM} = & -1^{A_2} & : & \beta v - A_2 \\ H_{t_3}^{LM} = & 0 & : & 0 \end{array} \tag{A4}$$

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where the execution probabilities are given by (4) and (5). Because $p^*_{t_3}(A_1|S_{t_3}) \neq 0$ *and* $p^*_{t_3}(B_k|S_{t_3}) \neq 0$, following Lemma 1 equilibrium strategies include both limit and market orders.[28] Moreover, given that the book is empty on the bid side, traders must also choose a degree of aggressiveness for their limit buy orders. Traders will optimally choose a more aggressive limit order at B_1 rather than a limit order at B_2 if $\exists\beta$ s.t. $(\beta v - B_1) \cdot p^*_{t_3}(B_1|[1010]) > \max\{\beta v - A_2,\ (\beta v - B_2) \cdot p^*_{t_3}(B_2|[1001])\}$. This implies that the threshold between $H_{t_3} = -1^{A_2}$ and $H_{t_3} = +1^{B_1}$ must be larger than the threshold between $H_{t_3} = -1^{A_2}$ and $H_{t3} = +1^{B_2}$. Specifically, as $\beta^{LM}_{+1^{B_k},-1^{A_2},t_3|[1000]} = \frac{A_2}{v} + \frac{p^*_{t_3}(B_k|S_{t3})}{1-p^*_{t_3}(B_k|S_{t_3})} \cdot \frac{A_2-B_k}{v}$, in order for $\beta^{LM}_{+1^{B_1},-1^{A_2},t_3|[1000]} > \beta^{LM}_{+1^{B_2},-1^{A_2},t_3|[1000]}$, the higher price (by one tick, τ) they pay if they choose a limit order at B_1 must be compensated by a higher execution probability. The relative tick size $\frac{\tau}{v}$ such that $\beta^{LM}_{+1^{B_1},-1^{A_2},t_3|[1000]} = \beta^{LM}_{+1^{B_2},-1^{A_2},t_3|[1000]}$ is $\frac{2}{3}(-5+2\sqrt{7}) \approx 0.19433$. Figure A.4 shows that for $\frac{\tau}{v} \in (0, 0.19433]$, $\beta^{LM}_{+1^{B_1},-1^{A_2},t_3|[1000]} < \beta^{LM}_{+1^{B_2},-1^{A_2},t_3|[1000]}$. Therefore, $H_{t_3} = +1^{B_1}$ is never optimal for $\frac{\tau}{v} \in (0, 0.1]$ if at t_3 the book opens empty on the bid side.[29] The equilibrium strategies at t_3 are: $H^{*LM}_{t_3}(\beta|[1000]) = \begin{cases} -1^{B_2} & \text{if } \beta \in [0, \beta^{LM}_{-1^{B_2},+1^{A_1},t_3|[1000]}) \\ +1^{A_1} & \text{if } \beta \in [\beta^{LM}_{-1^{B_2},+1^{A_1},t_3|[1000]}, \beta^{LM}_{+1^{A_1},+1^{B_2},t_3|[1000]}) \\ +1^{B_2} & \text{if } \beta \in [\beta^{LM}_{+1^{A_1},+1^{B_2},t_3|[1000]}, \beta^{LM}_{+1^{B_2},-1^{A_2},t_3|[1000]}) \\ -1^{A_2} & \text{if } \beta \in [\beta^{LM}_{+1^{B_2},-1^{A_2},t_3|[1000]}, 2] \end{cases}$

Considering that we are deriving the equilibrium strategies starting with a book that opens at t_3 with one share on A_2, we can now compute the execution probability of the strategy $H_{t_2} = +1^{A_2}$ that turned the book into $S_{t_2} = [1000]$:

$$\begin{aligned} p^*_{t_2}(A_2|[1000]) \quad = \quad & \frac{2-\beta^{LM}_{+1^{B_2},-1^{A_2},t_3|[1000]}}{2} + \frac{\beta^{LM}_{+1^{B_2},-1^{A_2},t_3|[1000]} - \beta^{LM}_{+1^{A_1},+1^{B_2},t_3|[1000]}}{2} \cdot p^*_{t_4}(A_2|[1000]) \\ & + \frac{\beta^{LM}_{-1^{B_2},+1^{A_1},t_3|[1000]}}{2} \cdot p^*_{t_4}(A_2|[1000]) \end{aligned} \tag{A.16}$$

The first term represents the probability that the limit sell order at A_2 gets executed at t_3 by a market order, whereas the other two terms are the probabilities of getting executed at t_4 after that at t_3 a limit order at B_2, or a market order to sell is submitted, respectively.

[28] Note that $p^*_{t_3}(A_2|S_{t_3}) = 0$ because the order already standing at A_2 has time priority: at t_4 the game ends and so there is only one trader left that could submit a market order to the ask side.

[29] Similarly, we can show that $H^{LM}_{t_3} = +1^{A_1}$ is never optimal if at t_3 the book opens empty on the ask side. An analogous result holds for the SM: if at t_3 the book opens empty, it is never optimal to post limit orders at a_l and b_l, for $l = 1, .., 4$.

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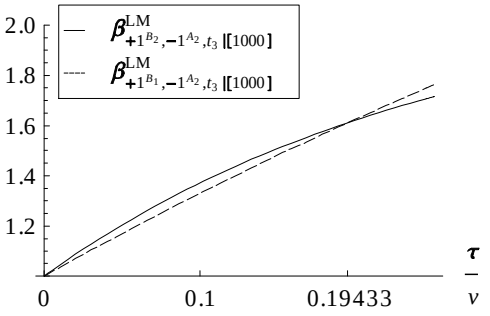


Figure A.4 - β-thresholds at t_3, $S_{t_2} = [1000]$.

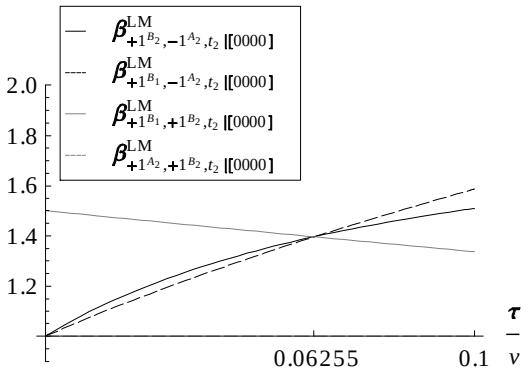


Figure A.5 - β-thresholds at t_2, $S_{t_1} = [0000]$.

Period t_2. Analogously, we compute the execution probabilities of the other limit order strategies to compare all possible traders' payoffs at t_2. As for t_3, Lemma 1 ensures that both limit and market orders are equilibrium strategies because $p^*_{t_2}(A_k|S_{t_2}) \neq 0$ *and* $p^*_{t_2}(B_k|S_{t_2}) \neq 0$. However, traders need to determine the level of aggressiveness of their limit orders. Consider and compare again the strategies on the bid side. For $H_{t_2} = +1^{B_1}$ to be an equilibrium strategy, the threshold between $H_{t_2} = +1^{B_1}$ and $H_{t_2} = -1^{A_2}$ must be larger than the threshold between $H_{t_2} = +1^{B_2}$ and $H_{t_2} = -1^{A_2}$.

We compute the value of the relative tick size such that the thresholds between a market buy order and a limit buy order at B_1 and B_2 respectively are equal, i.e., $\beta_{+1^{B_1},-1^{A_2},t_2|[0000]} = \beta_{+1^{B_2},-1^{A_2},t_2|[0000]}$, that is $\frac{\widehat{\tau}}{v}^{LM} \simeq 0.06255$. Figure A.5 shows that when $\frac{\tau}{v} \in (0, \frac{\widehat{\tau}}{v}^{LM})$, $\beta_{+1^{B_1},-1^{A_2},t_2|[0000]} < \beta_{+1^{B_2},-1^{A_2},t_2|[0000]}$ and $H_{t_2} = +1^{B_1}$ is not an equilibrium strategy. When instead $\frac{\tau}{v} \in [\frac{\widehat{\tau}}{v}^{LM}, 0.1]$, both $H_{t_2} = +1^{B_1}$ and $H_{t_2} = +1^{B_2}$ are equilibrium strategies: $\beta_{+1^{B_1},-1^{A_2},t_2|[0000]} > \beta_{+1^{B_2},-1^{A_2},t_2|[0000]}$, and $\beta_{+1^{B_1},+1^{B_2},t_2|[0000]} > \beta_{+1^{A_2},+1^{B_2},t_2|[0000]}$. In our numerical simulations, we assume that $\tau = 0.1$ so that $\frac{\tau}{v} \in [\frac{\widehat{\tau}}{v}^{LM}, 0.1]$ only for $v = 1$. So, at t_2 a limit order posted at B_1 conditional on $S_{t_1} = [0000]$ is optimal for $v = 1$ while it is not optimal for $v = 3$. We conclude that for $\frac{\tau}{v} \in (0, \frac{\widehat{\tau}}{v}^{LM})$ the equilibrium strategies are:

$$H^{*LM}_{t_2}(\beta, \tfrac{\tau}{v} \in (0, \tfrac{\widehat{\tau}}{v}^{LM})|[0000]) = \begin{cases} -1^{B_2} & \text{if } \beta \in [0, \beta^{LM}_{-1^{B_2},+1^{A_2},t_2|[0000]}) \\ +1^{A_2} & \text{if } \beta \in [\beta^{LM}_{-1^{B_2},+1^{A_2},t_2|[0000]}, \beta^{LM}_{+1^{A_2},+1^{B_2},t_2|[0000]}) \\ +1^{B_2} & \text{if } \beta \in [\beta^{LM}_{+1^{A_2},+1^{B_2},t_2|[0000]}, \beta^{LM}_{+1^{B_2},-1^{A_2},t_2|[0000]}) \\ -1^{A_2} & \text{if } \beta \in [\beta^{LM}_{+1^{B_2},-1^{A_2},t_2|[0000]}, 2] \end{cases} \tag{A7}$$

When instead $\frac{\tau}{v} \in [\frac{\widehat{\tau}}{v}^{LM}, 0.1]$, submitting limit orders to the first level of the book is

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optimal, and the equilibrium strategies at t_2 are:

$$H_{t_2}^{*LM}(\beta, \tfrac{\tau}{v} \in [\widehat{\tfrac{\tau}{v}}^{LM}, 0.1]|[0000]) = \begin{cases} -1^{B_2} & \text{if } \beta \in [0, \beta^{LM}_{-1^{B_2},+1^{A_1},t_2|[0000]}) \\ +1^{A_1} & \text{if } \beta \in [\beta^{LM}_{-1^{B_2},+1^{A_1},t_2|[0000]}, \beta^{LM}_{+1^{A_1},+1^{A_2},t_2|[0000]}) \\ +1^{A_2} & \text{if } \beta \in [\beta^{LM}_{+1^{A_1},+1^{A_2},t_2|[0000]}, \beta^{LM}_{+1^{A_2},+1^{B_2},t_2|[0000]}) \\ +1^{B_2} & \text{if } \beta \in [\beta^{LM}_{+1^{A_2},+1^{B_2},t_2|[0000]}, \beta^{LM}_{+1^{B_2},+1^{B_1},t_2|[0000]}) \\ +1^{B_1} & \text{if } \beta \in [\beta^{LM}_{+1^{B_2},+1^{B_1},t_2|[0000]}, \beta^{LM}_{+1^{B_1},-1^{A_2},t_2|[0000]}) \\ -1^{A_2} & \text{if } \beta \in [\beta^{LM}_{+1^{B_1},-1^{A_2},t_2|[0000]}, 2] \end{cases} \tag{A8}$$

Period t_1. To find the equilibrium strategies at the first period of the trading game we follow a similar procedure. These are:

$$H_{t_1}^{*LM}(\beta, \tfrac{\tau}{v} \in [\widehat{\tfrac{\tau}{v}}^{LM}, 0.1]|[0000]) = \begin{cases} -1^{B_2} & \text{if } \beta \in [0, \beta^{LM}_{-1^{B_2},+1^{A_1},t_1|[0000]}) \\ +1^{A_1} & \text{if } \beta \in [\beta^{LM}_{-1^{B_2},+1^{A_1},t_1|[0000]}, \beta^{LM}_{+1^{A_1},+1^{A_2},t_1|[0000]}) \\ +1^{A_2} & \text{if } \beta \in [\beta^{LM}_{+1^{A_1},+1^{A_2},t_1|[0000]}, \beta^{LM}_{+1^{A_2},+1^{B_2},t_1|[0000]}) \\ +1^{B_2} & \text{if } \beta \in [\beta^{LM}_{+1^{A_2},+1^{B_2},t_1|[0000]}, \beta^{LM}_{+1^{B_2},+1^{B_1},t_1|[0000]}) \\ +1^{B_1} & \text{if } \beta \in [\beta^{LM}_{+1^{B_2},+1^{B_1},t_1|[0000]}, \beta^{LM}_{+1^{B_1},-1^{A_2},t_1|[0000]}) \\ -1^{A_2} & \text{if } \beta \in [\beta^{LM}_{+1^{B_1},-1^{A_2},t_1|[0000]}, 2] \end{cases} \tag{A9}$$

A.2 Small Market (SM)

We solve the SM model in a similar way. Because the market starts at t_1 with a large tick size equal to $\tau_{LM}= \tau$, equilibrium strategies at t_1 are obtained as for the LM case with the difference that in the SM case traders expect that at t_2 the tick size will be reduced to $\tau_{SM}=\frac{\tau}{3}$. So the equilibrium strategies are qualitatively the same as both a limit order at the first level of the book or a limit order posted at the second level of the book are equilibrium strategies. So if for example a buyer arrives, the three possible states of the book are [0000], [0001] and [0010] for the LM and [00000 00000] [00000 00001] and [00000 01000] for the SM. We take the first case for abbreviation, [0]. We now directly present as an example the equilibrium strategies at t_2 for the book that opens empty, and that for brevity we indicate as $S_{t_1} = [0]$. The equilibrium strategies at t_2 differ depending on the relative tick size. By comparing the thresholds for the different limit order buy strategies, $H^{SM}_{t_2} = \{+1^{b_1}, +1^{b_2}, +1^{b_3}, +1^{b_4}, +1^{b_5}\}$, we obtain that when $\frac{\tau_{SM}}{v} \in (0, \widehat{\frac{\tau_{SM}}{v}})$, where $\widehat{\frac{\tau_{SM}}{v}} \simeq 0.07162$ is the value of the relative tick size such that the thresholds between a market buy order and a limit buy order at b_1 and b_5 respectively are equal, i.e.,

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$\beta_{+1^{b_1},-1^{a_5},t_2|[0]} = \beta_{+1^{b_5},-1^{a_5},t_2|[0]}$, traders submit limit orders only at b_5. Equilibrium strategies are: $H^{*SM}_{t_2}(\beta, \frac{\tau_{SM}}{v} \in (0, \widehat{\frac{\tau_{SM}}{v}})|[0]) = \{-1^{b_5}, +1^{a_5}, +1^{b_5}, -1^{a_5}\}$. When instead $\frac{\tau_{SM}}{v} \in [\widehat{\frac{\tau_{SM}}{v}}, 0.1]$, they increase the aggressiveness of their limit orders and equilibrium strategies at t_2 are: $H^{*SM}_{t_2}(\beta, \frac{\tau_{SM}}{v} \in [\widehat{\frac{\tau_{SM}}{v}}, 0.1]|[0]) = \{-1^{b_5}, +1^{a_1}, +1^{a_5}, +1^{b_5}\}$.

A.3 LM vs. SM

Consider period t_2 as an example. The optimal strategies for a book that starts empty at t_2 are:

	Case 1	Case 2
τ/v	$(0, 0.06255)$	$[0.06255, 0.07162)$
$H^{*LM}_{t_2}$	$-1^{B_2}, 1^{A_2}, 1^{B_2}, -1^{A_2}$	$-1^{B_2}, 1^{A_1}, 1^{A_2}, 1^{B_2}, 1^{B_1}, -1^{A_2}$
$H^{*SM}_{t_2}$	$-1^{b_5}, 1^{a_5}, 1^{b_5}, -1^{a_5}$	$-1^{b_5}, 1^{a_5}, 1^{b_5}, -1^{a_5}$

To compare the LM with the SM in terms of liquidity provision and volume, it is sufficient to compare the thresholds that make the trader indifferent between submitting a market order and the most attractive among the available limit orders. For the ask side, the equilibrium thresholds that we need to consider for the LM are $\beta^{LM}_{-1^{B_2},+1^{A_2},t_2|S_{t_2}}$ for Case 1, and $\beta^{LM}_{-1^{B_2},+1^{A_1},t_2|S_{t_2}}$ for Cases 2 and 3; while for the SM, $\beta^{SM}_{-1^{b_5},+1^{a_5},t_2|S_{t_2}}$ for Cases 1 and 2, and $\beta^{SM}_{-1^{b_5},+1^{a_1},t_2|S_{t_2}}$ for Case 3. As an example, we consider Case 3:

$$\beta^{LM}_{-1^{B_2},+1^{A_1},t_2|S_{t_2}} = \frac{B_2}{v} - \frac{p^*_{t_3}(A_1|S_{t_2})}{1-p^*_{t_3}(A_1|S_{t_2})} \cdot \frac{A_1 - B_2}{v} < \beta^{SM}_{-1^{b_5},+1^{a_1},t_2|S_{t_2}} \tag{A10}$$

The opposite holds for the bid side. Consequently, volume is lower in the LM:

$$VL^{LM}_{t_2|[0000]} = \frac{2-\beta^{LM}_{+1^{B_1},-1^{A_2},t_2|[0000]}}{2} + \frac{\beta^{LM}_{-1^{B_2},+1^{A_1},t_2|[0000]}}{2} < VL^{SM}_{t_2|[0]} \tag{A11}$$

When the book opens empty at t_2, $H_{t_2} = 0$ is never optimal and traders use only market and limit orders. Thus, because $VL^{LM}_{t_2|[0000]} < VL^{SM}_{t_2|[0]}$, we obtain that $LP^{LM}_{t_2|[0000]} > LP^{SM}_{t_2|[0]}$. Furthermore, when the book opens empty, total depth is equal to the liquidity provision so that $DPT^{LM}_{t_2|[0000]} > DPT^{SM}_{t_2|[0]}$. Inside depth also coincides with liquidity provision in this case, so that $DPI^{LM}_{t_2|[0000]} > DPI^{SM}_{t_2|[0]}$. Finally, we compute the spread:

$$\begin{aligned} SP^{LM}_{t_2|[0000]} &= E[A_{k'} - B_{k'}] \\ &< SP^{SM}_{t_2|[0]} \end{aligned} \tag{A12}$$

Because of the monotonicity of the β-thresholds, as visible for example in Figures A.1

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and A.2, these results hold for $\frac{\tau}{v} \in (0, 0.1]$. Similarly, we obtain analogous results for periods t_3 and t_4.

As for welfare, values for t_2 are computed by using (13) and (15). Results in Figure 2 are computed by solving the model for $\tau = 0.1$ and $v = \{1, 3\}$.

When the book opens at t_2 with one share on the first price level we obtain the opposite, i.e., that moving from the LM to the SM volume decreases and liquiidty provision increases, thus lowering the spread and increasing welfare.

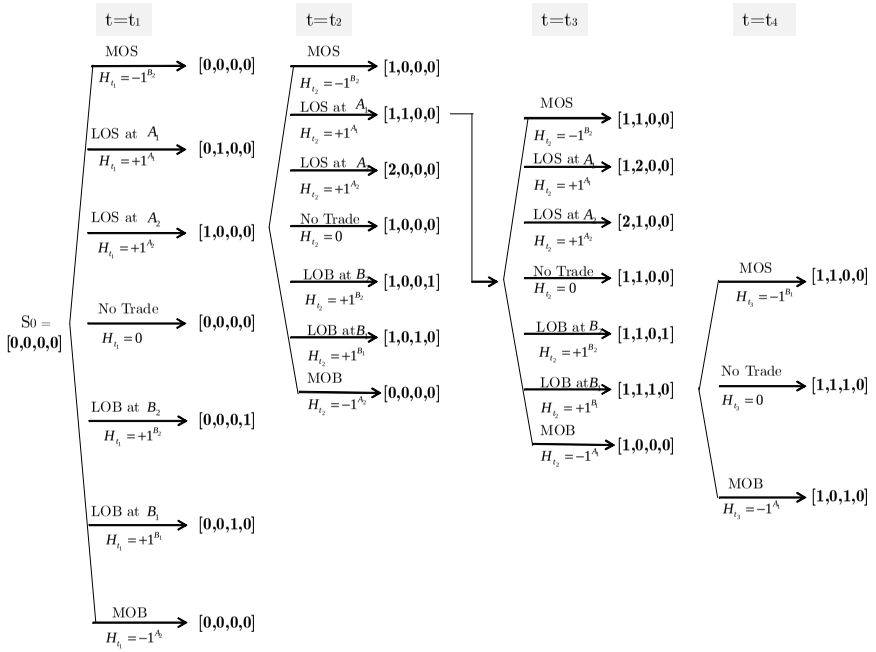
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Table 15: Order Submission Strategy Space.
This Table reportsin column 3 the payoffs, $U(\cdot)$,
In the case of market orders, $A_{k'}$ and $B_{k'}$ always
refer to the bestof the order strategies
H_t listed in column 1. ask and bid prices.

Strategy	H_t	$U(\cdot)$
Market Sell Order	$-1^{B_{k'}}$	$B_{k'} - \beta v$
Limit Sell Order	1^{A_k}	$p_t(A_k\|_{S_t}) \cdot (A_k - \beta v)$
No Trade	0	0
Limit Buy Order	1^{B_k}	$p_t(B_k\|_{S_t}) \cdot (\beta v - B_k)$
Market Buy Order	$-1^{A_{k'}}$	$\beta v - A_{k'}$

Figure 1: Extensive form of the game.
This figure reports an example from the extensive form of
the game. The bookopens at t_1 empty: $S_0 = [0, 0, 0, 0]$.
H_t refers to the strategy of the trader who arrives at the market
ìin period t. All available H_t are defined in Table 1



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Table 16: **Price Grids.**
This table shows the price grid for both the large (LM, with tick size equal to $\tau_{LM} = \tau = 0.1$) and the small tick market (SM, with tick size equal to $\tau_{SM} = \frac{\tau}{3}$) under the assumption that v=1 (left) and $v = 3$ (right). In both protocols the price improvement (PI) is equal to 30% of the asset value,v.

a5	1+9/2 x 0.1/3	1.15	A2	1+3/2 x 0.1	1.15
a4	1+7/2 x 0.1/3	1.12			
a3	1+5/2 x 0.1/3	1.08			
a2	1+3/2 x 0.1/3	1.05	A1	1+1/2 x 0.1	1.05
a1	1+1/2 x 0.1/3	1.02			
v=1			v=1		
b1	1-1/2 x 0.1/3	0.98			
b2	1-3/2 x 0.1/3	0.95	B1	1-1/2 x 0.1	0.95
b3	1-5/2 x 0.1/3	0.92			
b4	1-7/2 x 0.1/3	0.88			
b5	1-9/2 x 0.1/3	0.85	B2	1-3/2 x 0.1	0.85

3 ticks = 0.3 = PI

SM $\tau_{SM} = \frac{0.1}{3}$ LM $\tau_{LM} = 0.1$

$\tau_{SM} = \frac{0.1}{3}$ v=3			$\tau_{LM} = 0.1$ v=3		
a14	…	3.45	A5	3+9/2 x 0.1	3.45
a13					
a12					
a11		3.35	A4	3+7/2 x 0.1	3.35
a10					
a9					
a8	…	32.5	A3	3+5/2 x 0.1	3.25
a7	…				
a6	…				
a5	3+9/2 x 0.1/3	3.15	A2	3+3/2 x 0.1	3.15
a4	3+7/2 x 0.1/3	3.12			
a3	3+5/2 x 0.1/3	3.08			
a2	3+3/2 x 0.1/3	3.05	A1	3+1/2 x 0.1	3.05
a1	3+1/2 x 0.1/3	3.02			
v=3			v=3		
b1	3-1/2 x 0.1/3	2.98			
b2	3-3/2 x 0.1/3	2.95	B1	3-1/2 x 0.1	2.95
b3	3-5/2 x 0.1/3	2.92			
b4	3-7/2 x 0.1/3	2.88			
b5	3-9/2 x 0.1/3	2.85	B2	3-3/2 x 0.1	2.85
b6	…				
b7	…				
b8	…	2.75	B3	3-5/2 x 0.1	2.75
b9	…				
b10					
b11		2.65	B4	3-7/2 x 0.1	2.65
b12					
b13					
b14	…	2.55	B5	3-9/2 x 0.1	2.55

9 ticks = 0.9 = PI

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Table 17 LM This Table shows the Large Market (LM) order submission strategies at t_2 that result in equilibrium when the book opens at the end of period t_1 either with 1 share on $A_1$and no shares on the other price levels, or with no shares on any price level (empty book), which for simplicity we report as [01 00] and [0000] respectively, with the trading crowd, TC, sitting at A_2 and B_2. These are the states of the book that derive from two of the three equilibrium strategies that traders choose at t_1 on the ask side, i.e., a limit order at A_1 and a market order at B_2,the third strategy being a limit order at A_2 that we discuss in the Appendix. Because at t_1 the book opens empty, the equilibrium strategies from the bid side are symmetric. LO indicates a limit order and MO a market order; for example, LOA_2 indicates a limit order of 1 share posted at A_2. Our measure of expected aggregate depth is equal to the sum of the probability that at the end of t_2 there will be 1 share at each price level; for example, depth at A_2 is equal to 1 times that probability that a LO is posted at A_2; whereas depth at A_1 is equal to the probability that at the end of t_2 the book has 1 share at the price level A_1; this happens conditional on all the equilibrium strategies with the exception of MOA_1, i.e., when the order consumes the liquidity standing on A_1. The other measures of market quality, depth at the best bid offer (DepthBBO),spread (S) and Volume are reported in the lower part of the table, whereas our measure of expected welfare $E(W_t)$ is equal to the sum of the agents' expected gains from both market and limit orders (Equation 13 in the text). The stock price is $v = 1$, the tick size is $\tau_{LM}= \tau = 0.1$ and the relative tick size is $\frac{\tau_{LM}}{v} = \frac{\tau}{v} = 0.1$.

Price level	Strategy at t_2		State of the Book after strategy at t_2		Order Submission Probability at t_2		Depth Price Levels at t_2	
	[0100]	[0000]	[0100]	[0000]	[0100]	[0000]	[0100]	[0000]
$A_2= v+\frac{9}{6}\tau$	LOA_2	MOA_2	[11 00]	[00 00]	0.063	0.207	TC	TC
		LOA_2		[10 00]		0.168	0.063	0.168
$A_1= v+\frac{3}{6}\tau$	MOA_1	LOA_1	[00 00]	[01 00]	0.306	0.125	0.694	0.125
							(1-PrMOA_1)	
$B_1= v-\frac{3}{6}\tau$		LOB_1		[00 10]		0.125		0.125
$B_2= v-\frac{9}{6}\tau$	LOB_2	LOB_2	[01 01]	[00 01]	0.237	0.168	0.237	0.168
	MOB_2	MOB_2	[01 00]	[00 00]	0.394	0.207	TC	TC
					1	1	Agg.Depth=0.994	Agg.Depth=0.586

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Table 18 SM This Table shows the Small Market (SM) order submission strategies at $t_{\mathbf{2}}$ that result in equilibrium when the book opens at the end of period $t_{\mathbf{1}}$ either with 1 share on $a_1$and no shares on the other price levels, or with no shares on any price level (empty book), which for simplicity we report as [0001 ..] and [0000 ..] respectively, with the trading crowd, TC, sitting at a_5 and b_5. These are the states of the book that derive from two of the three equilibrium strategies that traders choose at $t_{\mathbf{1}}$ on the ask side, i.e., a limit order at A_1 and a market order at B_2,the third strategy being a limit order at A_2 that we discuss in the Appendix. Because at t_1 the book opens empty, the equilibrium strategies from the bid side are symmetric. LO indicates a limit order and MO a market order; for example, LOa_2 indicates a limit order of 1 share posted at a_2. Our measure of expected aggregate depth is equal to the sum of the probability that at the end of $t_{\mathbf{2}}$ there will be 1 share at each price level; for example, depth at a_1 is equal to 1 times that probability that a LO is posted at a_1; whereas depth at a_2 is equal to the probability that at the end of $t_{\mathbf{2}}$ the book has 1 share at the price level a_2; this happens conditional on all the equilibrium strategies with the exception of MOa_2, i.e., when the order consumes the liquidity standing on a_2. The other measures of market quality, depth at the best bid offer (DepthBBO),spread (S) for $\tau_{SM} = \frac{0.1}{3}$, spread (S') for $\tau_{SM} = 0.1$,Relative Spread and Volume are reported in the lower part of the table, whereas our measure of expected welfare $E(W_t)$ is equal to the sum of the agents' expected gains from both market and limit orders (Equation 13 in the text). AgD stays for aggregate depth The table reports results for a relative tick size equal to $\frac{\tau_{SM}}{v} = \frac{\tau}{v} = \frac{0.1}{3}$ that can result either from the framework with $v = 1$ and the tick size is $\tau_{SM} = \frac{\tau}{3} = \frac{0.1}{3}$, or from the framework $v = 3$ and the tick size is τ_{SM}= $\tau = 0.1$. Note that only the quoted spread differs and is therefore reported separately. Note no order submission strategies at a_3, a_4, b_2, b_3,and b_4.

Price level	Strategy at $t_{\mathbf{2}}$		State of the Book after strategy at $t_{\mathbf{2}}$		Order Submission Probability at $t_{\mathbf{2}}$		Depth Price Levels at $t_{\mathbf{2}}$	
	[10000..]	[00000..]	[10000..]	[00000..]	[10000..]	[00000..]	[10000..]	[00000..]
a_5= v+$\frac{9}{6}\tau$		MOa_5		[00000 00000]		0.221	TC	TC
		LOa_5		[10000 00000]		0.190		0.190
a_2= v+$\frac{3}{6}\tau$	MOa_2		[00000 00000]		0.340		0.660(1-PrMOa_2)	
a_1= v+$\frac{1}{6}\tau$	LOa_1	LOa_1	[00011 00000]	[00001 00000]	0.250	0.089	0.250	0.089
b_1= v−$\frac{1}{6}\tau$		LOb_1		[00000 10000]		0.089		0.089
b_5= v−$\frac{9}{6}\tau$	LOb_5	LOb_5	[00010 00001]	[00000 00001]	0.189	0.190	0.189	0.190
	MOb_5	MOb_5	[00010 00000]	[00000 00000]	0.221	0.221	TC	TC
					1	1	AgD=1.099	AgD=0.558

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Table 19 Panel A - LSE Group definitions This table reports descriptive statistics for the four groups of LSE stocks used for the RDD. We report the price of the stock in GBX, bid depth in number of shares, quoted spread in GBX, relative spread in percentage, volume in number of shares, market capitalization in GBP Millions, and the value of the tick size below and above the threshold considered. For relative spread, quoted spread, bid depth and volume we report the daily average and for market capitalization we report the value at the beginning of 2013.

Price (GBX)	Number of stocks	Tick Size TS (GBX)	Bid Depth (# of shares)	Quoted Spread (GBX)	Relative Spread (%)	Volume (# of shares)	Market Capitalization (M GBP)
1000	41	TS above 1	2,667	4.62	0.45	802,958	2,779
		TS below 0.5	1,755	3.97	0.40	640,033	
500	60	TS above 0.5	2,975	2.53	0.50	771,363	2,444
		TS below 0.1	1,750	2.39	0.48	751,679	
100	21	TS above 0.1	12,327	0.36	0.35	2,935,986	1,317
		TS below 0.05	9,047	0.35	0.35	4,076,990	
10	20	TS above 0.25	5,008	0.52	3.71	2,596,996	104
		TS below 0.01	3,728	0.38	4.56	2,627,796	

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Table 19 Panel B - This table reports descriptive statistics for the group of Nasdaq stocks used for the RDD. We report the price of the stock in $, bid depth in number of shares, quoted spread in $ cents, relative spread in $ cents/$, volume in number of shares, market capitalization in $ Millions and the value of the tick size below and above the threshold considered. For relative spread, quoted spread, bid depth and volume we report the daily average and for market capitalization we report the value at the end of September 2010.

Price ($)	Number of Stocks	Tick Size ($ cents)	Bid Depth (# shares)	Quoted Spread ($ cents)	Relative Spread (cents/$)	Volume (# shares)	Market Capitalization (M $)
1	20	TS above 1	1,117	1.76	1.41	245,238	45.6
		TS below 0.01	821	0.99	1.19	202,480	

Table 5 Panel C - This table reports descriptive statistics for the Nasdaq and NYSE stocks used for the Fama MacBeth regression. We report the price of the stock in $, bid depth in number of shares, quoted spread in $ cents, relative spread in $ cents/$, volume in number of shares and market capitalization in $ Millions. For relative spread, quoted spread, bid depth and volume we report the daily average and for market capitalization we report the value at the end of September 2010.

Price ($)	Number of Stocks	Bid Depth (# shares)	Quoted Spread ($ cents)	Relative Spread (cents/$)	Volume (# shares)	Market Capitalization (M $)
29.70	180	15,064	3.96	0.15	5,923,018	7,330

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Table 20 RDD: 500 GBX This table reports the results of regression discontinuity for bid depth, quoted and relative spread for the group of stocks that crosses the 500 GBX threshold. We estimate the following panel regression model:

$$y_{i,t} = b_i + b_1 D_{i,t} + b_2(price_{i,t} - c) + b_3(price_{i,t} - c)D_{i,t} + \varepsilon_{i,t}$$

where $price_{i,t}$ is the price. $D_{i,t}$ is an indicator that takes the value of 1 if $price_{i,t}$ is equal to or greater than c and a value of 0 if $price_{i,t}$ is less than c. $price_{i,t}$ is reduced by c to have the threshold at zero. c is 500. $y_{i,t}$ can be either quoted spread, or relative spread, or bid depth, or volume. Estimation is done using a panel regression with standard errors clustered by stock. Results are reported for a bandwidth of 1%.

	Bid Depth	Quoted Spread	Relative Spread	Volume
Price	106.9633***	-0.1072**	-0.0002**	1013.9381
	(3.00)	(-2.16)	(-2.23)	(1.54)
Dummy	1311.2409***	0.4861***	0.0010***	-10631.7767**
	(4.94)	(3.02)	(3.03)	(-3.35)
Price*Dummy	-713.225	0.0498	0.0001	1385.0356
	(-1.00)	(1.02)	(1.08)	(1.20)
Observations	33736	33736	33736	25815
FE	Yes	Yes	Yes	Yes
R^2	0.2008	0.7049	0.7062	0.0182

t statistics in parentheses

* p<0.10, ** p<0.05, *** p<0.01

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Table 21 LSE Stocks This table reports the sign and significance level of the regression coefficients from the regression discontinuity for BBO depth as well as for Quoted Spread and Relative Spread. We estimate the following panel OLS regression model:

$$y_{i,t} = b_i + b_1 D_{i,t} + b_2(price_{i,t} - c) + b_3(price_{i,t} - c)D_{i,t} + \varepsilon_{i,t}$$

where $price_{i,t}$ is the price. $D_{i,t}$ is an indicator that takes the value of 1 if $price_{i,t}$ is equal to or greater than c and a value of 0 if $price_{i,t}$ is less than c. $price_{i,t}$ is reduced by c to have the threshold at zero. c can be 10, 100, 500 or 1000 depending on the group. $y_{i,t}$ can be bid depth, quoted spread or relative spread. Estimation is done using a panel regression with standard errors clustered by stock. Column 1 reports the stock price, columns 2, 4 and 6 report the sign and significance level of the b_1 coefficient and columns 3, 5 and 7 report whether the coefficient is significant for the bandwidth of 1%, 2% and 3% respectively: 3/3 means that the coefficient is significance (labeled as Significant.) for all the three bandwidths.

	Bid Depth		Quoted Spread		Relative Spread		Volume	
Stock Price	Signific.	Bandwidths	Signific.	Bandwidths	Signific.	Bandwidths	Signific.	Bandwidths
10 GBX	+|*	(3/3)	+|*	(2/3)	+|*	(2/3)	-	
100 GBX	+|*	(1/3)	+|***	(2/3)	+|***	(2/3)	-	
500 GBX	+|***	(3/3)	+|***	(1/3)	+|***	(1/3)	-|***	(3/3)
1000 GBX	+|***	(3/3)	+|***	(3/3)	+|***	(3/3)	-|***	(2/3)

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Table 22 RDD - Nasdaq Stocks: Bid Depth, Quoted and Relative Spread This table reports the results of regression discontinuity for the bid depth. We estimate the following panel regression model:

$$y_{i,t} = b_i + b_1 D_{i,t} + b_2(price_{i,t} - 1) + b_3(price_{i,t} - 1)D_{i,t} + \varepsilon_{i,t}$$

where $price_{i,t}$ is the price rounded down to the closest cent. $D_{i,t}$ is an indicator that takes the value of 1 if $price_{i,t}$ is equal to or greater than \$1 and a value of 0 if $price_{i,t}$ is less than \$1. $price_{i,t}$ is reduced by one to have the threshold at zero. $y_{i,t}$ is the logarithm of the bid depth and of relative spread respectively. Estimation is done using a panel regression with standard errors clustered by stock. Estimation is carried out for three different bandwidths (10%, 15% and 7.5% of \$1). Volume has been aggregated in bins of width 1 cent for each day.

	Bandwidth:10%			Bandwidth: 15%			Bandwidth: 7.5%		
	Bid Depth	Quoted spread	Volume	Bid Depth	Quoted Spread	Volume	Bid Depth	Quoted Spread	Volume
Price	-1.46	-0.083	182136.6	-2.82	-0.094	32432.1	-1.92	-0.043	274809.9*
	(-0.48)	(-1.07)	(1.66)	(-1.54)	(-1.64)	(0.58)	(-0.41)	(-0.52)	(1.92)
Dummy	1.57***	0.013*	10892.3	1.46***	0.014*	17398.0	1.55***	0.013**	7016.2
	(4.46)	(2.28)	(1.80)	(4.29)	(2.52)	(1.65)	(3.95)	(2.88)	(1.34)
Price*	-8.53	0.11	-142930.4	-2.30	0.09	-19678.5	-6.49	0.015	-205926.6
Dummy	(-1.43)	(0.66)	(-1.64)	(-0.48)	(0.85)	(-0.33)	(-0.80)	(0.07)	(-1.51)
FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	1887	1887	2442	2483	2483	3352	1532	1532	1941
R^2	0.23	0.52	0.09	0.19	0.51	0.08	0.24	0.51	0.09

t statistics in parentheses

*p<0.05, **p<0.01, ***p<0.001

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Table 23 Nasdaq and NYSE sample. BBO Depth. This table reports the results of regressions of the log of BBO depth, Quoted Spread, Relative Spread and log of Share Volume on contemporaneous market characteristics based on daily cross-sectional Fama-MacBeth regressions. We take the log of volume and BBO depth. The relative order imbalance is the absolute value of (buys-sells)/share volume. The intraday price range is defined as (high-low)/high. NYSE is a dummy variable which takes the value of 1 for stocks whose primary listing exchange is NYSE. We report the average daily coefficients on top and p-values below, computed accordingly Newey-West with 5 lags.

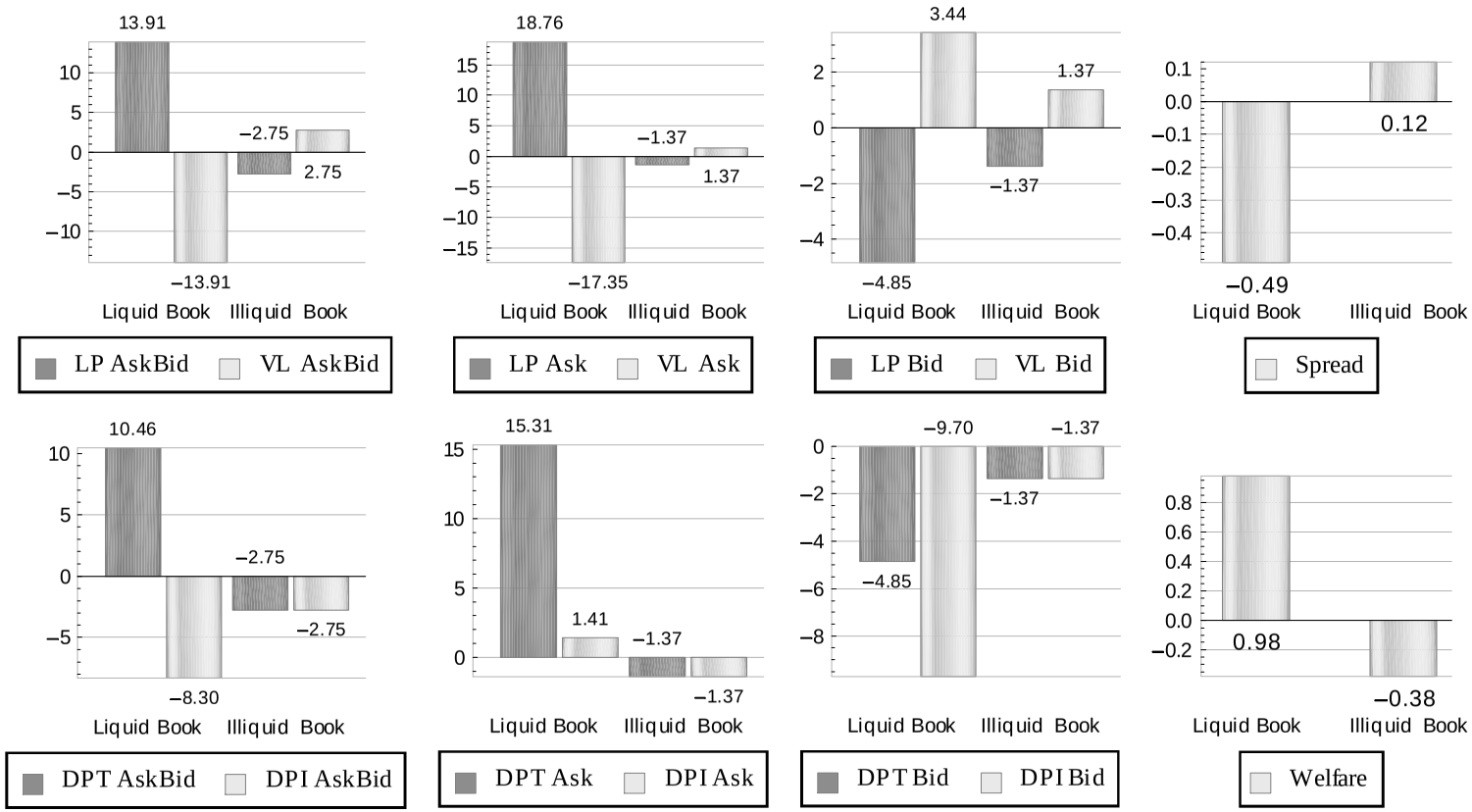
	BBO Depth	Quoted spread	Relative spread	Share Volume
NYSE	0.0078	0.18**	-0.016***	-0.017
	(0.620)	(0.010)	(0.000)	(0.327)
share volume (TAQ)	0.70***	-2.66***	-0.074***	-0.11***
	(0.000)	(0.000)	(0.000)	(0.000)
closing price (CSRP)	-0.033***	0.19***	0.00033***	0.031***
	(0.000)	(0.000)	(0.000)	(0.000)
quoted spread cents (TAQ)	0.075***	2.52***	0.068***	1.00***
	(0.000)	(0.000)	(0.000)	(0.000)
relative order imb. in % (TAQ)	-0.73***	0.43	0.044***	2.20***
	(0.000)	(0.350)	(0.001)	(0.000)
(high-low)/high (TAQ)	-6.67***	75.7***	2.24***	4.42***
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	7560	7560	7560	7560

p-values in parentheses
*p<0.05, **p<0.01, ***p<0.001

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Figure 2 LM –> SM - Liquid and Illiquid Book

This Figure reports statistics for order flows, market quality and welfare at t_2 that result from the comparison between the large tick market (LM) with $\tau_{LM} = \tau = 0.1$, and the small tick market (SM) which starts at t_1 with a large tick size equal to 0.1 and has the tick size reduced to $\tau_{SM} = \frac{\tau}{3} = \frac{0.1}{3}$ from period t_2 onwards. We consider the two regimes of "Liquid book" and "Illiquid book", and the asset values equal to $v = 1$.



Chapter 3

Sub-Penny and Queue-Jumping

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Sub-Penny and Queue-Jumping

Francesco Consonni, Ingrid M. Werner,
Yuanji Wen, Barbara Rindi, Sabrina Buti*

July 2015

Abstract

We develop a model where a public limit order book (PLB) competes with a Sub-Penny Venue, which allows Sub-Penny Trading (SPT). SPT occurs when a trader undercuts orders in the PLB by less than one penny, a practice we call queue jumping (QJ). QJ is higher for NASDAQ than for NYSE stocks. We confirm the model's predictions that QJ increases in liquidity and in the tick-to-price ratio. We also find that QJ is associated with improved PLB market quality, especially for large capitalization stocks. Finally, we show that High Frequency Trading is negatively related to QJ.

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3.1 Introduction

On January 15, 2015, a dark pool operator was fined $14.4 million by the U.S. Securities and Exchange Commission (SEC) for violating Rule 612 of Regulation National Market System (Reg NMS).[1] Rule 612 states that no market participant can accept, rank, or display orders priced in sub-pennies. However, between May 2008 and March 2011, the SEC alleges that the operator was accepting and ranking hundreds of millions of orders submitted to their dark pool that were priced in increments smaller than one cent.[2] Select market makers and High Frequency Traders (HFTs) were encouraged by the operator to use sub-penny orders, and were thereby able to undercut orders submitted to exchanges and Alternative Trading Systems (ATSs) without having to offer economically meaningful price improvement. Sub-penny orders helped these market makers and HFTs gain priority over resting orders in the Public Limit Order Book (PLB) queue at the full tick, and enabled HFTs to interact with uninformed order flow in the operator's dark pool. At the same time, the operators' clients using the firm's proprietary algorithms for order routing and execution logic were able to opt out of having their orders executing against market makers and HFTs in the operator's ATS by using restrictions on their orders. The SEC further argues that the operator introduced sub-penny orders without properly disclosing the nature of these order types to the SEC or to other traders using their dark pool. Finally, the SEC argues that the sub-penny order types created an unfair competitive advantage for the operator's dark pool relative to the venues that adhered to Rule 612.

The dark pool sub-penny trades (SPT) discussed above would have been printed off-exchange to one of the Trade Reporting Facilities (TRFs). NYSE's Trade and Quote (TAQ) data shows that such trades represented approximately 10% of the U.S. consolidated equity volume in 2010. Note that the fact that we see significant volume of sub-penny trades printed off-exchange does not necessarily mean that violations of Rule 612 occurred. The Rule allows broker-dealers to execute non-displayed orders (typically retail orders) by matching orders internally at sub-penny prices, against

[1] http://www.sec.gov/news/pressrelease/2015-7.html#.VP4D8eFzKZR

[2] The dark pool operator created two specific order types that resulted in sub-penny executions. The Whole Penny Offset (WPO) orders were available between 2008 and June 2010, and allowed a subscriber to submit orders priced at the National Best Bid (NBB) plus $0.01, the National Best Offer (NBO) minus $0.01 or at the midpoint of the NBBO plus or minus $0.01. If the NBBO was an odd number of cents, the WPO orders would have resulted in sub-penny orders. The PrimaryPegPlus (PPP) orders were introduced in June 2010 and allowed a subscriber to submit orders priced as a percentage of the NBBO plus or minus. For example, if the NBBO was $50.00 to $50.02 a PPP 10% plus buy order would mean an order to buy at $50.002. In addition, technical glitches in the operator's smart order routing (SOR) and algorithmic execution systems produced sub-penny executions.

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other clients' orders, or against their own inventory, as long as these orders obtain price improvement.[3] Furthermore, the SEC permits two specific types of sub-penny executions under Rule 612: mid-quote executions and execution at a price determined through a volume-weighted-average-price (VWAP) algorithm.[4] While these types of sub-penny executions are permitted by the Rule, they have the same negative effect on orders at the front of the queue on the PLB, i.e., they are undercut by an economically insignificant amount.

In this paper, we develop a model where a PLB faces competition from a Sub-Penny Venue (SPV). The SPV allows broker-dealers to submit orders on a finer grid to gain priority over resting orders in the PLB queue at the best bid or offer, and we call this phenomenon queue-jumping (QJ). We rely on the model to develop hypotheses about the factors influence the extent of QJ, and about the effects of QJ on market quality. We then test the model's predictions using TAQ data.

Rule 612 was introduced to limit the negative effects of decimalization which took place in 2001 for U.S. stocks.[5] The rationale for decimalization was to lower trading costs, and the empirical evidence shows that quoted and effective spreads indeed fell following decimalization (e.g., Chakravarty, Harris and Wood (2001), Bacidore, Battalio and Jennings (2003), and Bessembinder (2003)). However, decimalization also reduced PLB inside depth and increased market maker participation suggesting that undercutting may have had a detrimental effect on public liquidity provision (SEC, 2012). The SEC realized that if traders could undercut limit orders sitting on the book by an economically insignificant amount, it would potentially reduce the incentive for traders to post limit orders at the top of the PLB, and therefore could have a detrimental effect on inside depth. The SEC also realized that a smaller tick size and hence a lower inside spread would lead to lower profit opportunities for brokers. For these reasons, the SEC adopted Rule 612 which defines the minimum price increment of \$0.01 (1 penny) for stocks priced over \$1, and a minimum price increment of \$0.0001 for stocks priced below \$1.

The SEC's allegations in the Rule 612 violation case discussed above suggest

[3]Broker-dealers' internalization accounts for a substantial share of the U.S. consolidated equity volume according to the Securities and Exchange Commission's Concept Release on Equity Market Structure (SEC, 2010), being equal to 17.5% in 2009. According to the SEC Concept Release, in 2009 around 10 exchanges, 5 electronic communication networks, 32 dark pools, and over 200 broker-dealers were active in the U.S.

[4]Further, on July 3, 2012, the SEC issued a new rule that allowed exchanges to provide retail price improvement in sub-penny increments (units of \$0.001). NYSE started their Retail Liquidity Program (RLP) and NASDAQ their Retail Price Improvement (RPI) program under this rule. Trades in an approved retail price improvement program are printed on exchanges, and are excluded from our empirical analysis.

[5]In the U.S. from 2001 the minimum price improvement was gradually reduced to 1 cent for stocks above \$1 and 0.01 cent for stocks below \$1.

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that QJ through the use of dark pools is particularly important for traders pursuing algorithmic and HFT strategies. Fast trading includes smart order routers (SORs) which are programs largely used by both the buy and the sell side to search for the best quotes in regular exchanges as well as in dark pools. Therefore, the use of SORs guarantees that orders posted at sub-penny increments are actually executed if they offer the best price. We believe that this is a major reason for why dark trading combined with fast trading facilities has paved the way for the expansion of SPT.

For all the reasons discussed above, SPT is one of the main concerns of the SEC and in this paper we aim to study SPT in NASDAQ and NYSE stocks with the objective to understand the frequency of SPT, the factors which induce traders to undertake SPT and the effects that SPT has on market quality. We draw our main empirical hypotheses from a theoretical framework that extends Parlour (1998) to model competition between a PLB and a SPV. We distinguish between cases where the PLB is liquid (there are resting orders at the top of the book, i.e., the stock is tick-constrained) and those for which the PLB is illiquid (there are no orders resting on the top of the book, i.e., the stock is not tick-constrained). The model predicts that QJ is higher for liquid books (high depth and narrow spread) and for stocks with a high tick-to-price ratio, i.e., a low price for a given tick size.

Our empirical analysis is based on a sample of TAQ data for U.S. equities that includes all trades executed in sub-penny increments during 42 trading days in 2010. We include all regular trades printed to a TRF. Note that these trades may come either from broker-dealers' internalization or from trades executed in dark pools. We build a stratified sample of 90 NASDAQ and 90 NYSE listed stocks and use daily Fama-MacBeth regressions to investigate which factors are associated with more SPT, i.e., under which market conditions more sub-penny orders execute. We consider the influence of spread, depth, stock price, share volume, volatility and order imbalance on SPT. To understand the influence of SPT on market quality measured as spread and depth, we use a simultaneous equations model that controls for endogeneity. Finally, the SEC allegation suggests an important link between SPT and HFT, and we therefore investigate the relationship between HFT and SPT based on a commonly used proxy for HFT – the number of quote updates relative to trades.

Before summarizing the main results of the paper, it is important to explain how we classify SPT. We generally classify an execution as SPT when the price improvement associated to the execution price is smaller than \$0.01. However, note that there are two main reasons for why we observe trades executed on ATSs at fractions of a penny. First, traders may aim to undercut orders posted at the top of

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transparent PLBs. Second, the execution system of some dark pools and broker-dealer internalization systems follows a derivative pricing rule according to which all trades in execute at the midpoint of the primary market inside spread.[6] Note that while undercutting at sub-penny increments smaller than the distance to the midpoint of the PLB spread ostensibly permits traders to provide two-sided liquidity inside the PLB spread. By contrast, midpoint executions do not allow traders to capture a spread by simultaneously posting buy and sell orders. To differentiate between these two categories of SPT, we treat executions at half a cent price improvement as a separate type of SPT and name it Mid-Crossing (MID). [7] We group the remaining SPT with a positive sub-penny price improvement different from half-cent into a category that we label Queue-Jumping (QJ). This way we adopt a parsimonious classification of QJ, and do not mix data which derive from potentially different trading strategies that could have different driving forces and different effects on the quality of the lit markets. However, we acknowledge that by doing so we miss the executions originating from undercutting at exactly half a penny.[8]

Our empirical results regarding the determinants of QJ can be summarized as follows. We find that QJ is on average 7.16% of the consolidated volume for NASDAQ stocks and 6.03% for NYSE stocks. Consistently with the model's predictions, QJ is positively related to the liquidity of the book (depth) and the cent quoted spread, and this is true even after controlling for factors shown in the previous literature (e.g., Buti, Rindi, and Werner (2011)) to affect dark trading. Further, QJ is increasing in depth and in the spread both for NYSE and NASDAQ-listed stocks.. However, while QJ is increasing in depth for stocks in all size groups, the quoted cent spread does not significantly influence QJ for large stocks.

We also use the model to study the effects of QJ on market quality. The model predicts that QJ is associated with improved market quality – higher depth and narrower quoted PLB spreads - for liquid books. By contrast, QJ is predicted to be associated with worse market quality for illiquid books. Moreover, the model predicts that while PLB volume is lower, consolidated volume is higher in the presence of QJ as more traders switch to market orders when the risk of undercutting increases. Finally, the model predicts that the effects of QJ on market quality are dampened if the tick size in the PLB is lower.

As QJ and order submissions to the PLB are jointly determined, we need to

[6]To mention but a few, see ITG Posit, Liquidnet and BATS.

[7]While not included in our dataset, mid-quote executions can also occur within exchange operated dark pools.

[8]We also miss instances of QJ in stock at the whole penny increment, which may occur in high-priced and wide-spread stocks.

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account for endogeneity when empirically assessing the impact of QJ on market quality. To examine this question, we therefore estimate a simultaneous equation system following Hasbrouck and Saar (2013). As predicted by the model, we find that QJ is generally associated with higher depth and narrower quoted and relative spread. However, closer scrutiny shows that this result is driven by large capitalization stocks. We do not find significant results for the relationship between QJ and market quality for the group of small stocks, presumably because these stocks are less likely to be tick-constrained so that traders can undercut without executing in sub-penny.

We also show that MID executions represent 3.16% of the consolidated volume for NASDAQ stocks and 3.51% of the volume for NYSE stocks. MID executions also increase with depth and the cent quoted spread for the overall sample, and these results are also robust to controlling for the listing exchange, volatility and order imbalance. However, MID executions decrease in depth and cent quoted spread for NASDAQ and small cap stocks, and neither variable significantly influences MID for large stocks. Moreover, MID executions have no significant effects on market quality, measured either by depthor quoted spread. This is true for the overall sample as well as the subsamples by listing exchange and size.

The incentives for QJ is related to the tick size, and more specifically to the tick-to-price ratio. Two opposite proposals have been put forward from regulators and exchange officials that relate to SPT and the tick size. In 2010, the SEC in its Concept Release on Equity Market Structure stressed that the larger percentage spread that characterizes low-priced stocks may lead to greater internalization by Over-The-Counter (OTC) market makers or more trading volume in dark pools, and proposed a reduction in the tick size for lower priced stocks. While major U.S. exchanges, e.g., NYSE, NASDAQ and BATS, in their comment letters to the SEC Concept Release responded positively to the suggestion of reducing the tick size, there was at the same time a widespread sentiment among practitioners that decimalization curtailed brokers' profits and therefore incentives to supply liquidity for less liquid stocks and for initial public offerings (IPOs). This led Congress to pass the 2012 Jumpstart Our Business Startups Act (Section 106(b) of the "JOBS Act") which instructed the SEC to investigate the possible effects of raising the minimum price increment, i.e., the tick size, for stocks of high growth companies and authorized the SEC to conduct a pilot study to raise the tick size for small and medium capitalization stocks to \$0.05.

This tick-size debate motivates an investigation into whether an increase or a decrease in the tick size is the optimal regulatory response to the widespread use of SPT. The SEC concept release and the ensuing comment letters from market

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participants, as well as the predictions from our model, stress that it is the tick-to-price ratio that matters for policy. It follows that the size of the minimum tick size relative to the price of the stock is the relevant policy instrument in the context of SPT.[9] We therefore study the relationship between relative tick size (i.e., price) and QJ and MID based on daily Fama-Macbeth regressions, controlling for share volume. We find a strong negative empirical relationship between the stock price and QJ after controlling for share volume and listing exchange. By contrast, MID execcutions are not significantly influnced by the stock price for the overall sample, but are significantly positively related to price NASDAQ and small cap stocks. Furthermore, both QJ and MID increases significantly in share volume, controlling for listing exchange. Because the sample of NASDAQ and NYSE stocks includes only stocks priced above $1, the tick size is constant at $0.01 and therefore when the price increases the tick-to-price ratio decreases. In other words, we find a positive empirical relationship between QJ and the tick-to-price ratio as predicted by our model. If the aim of the SEC is to reduce QJ, our empirical results suggest that the right policy action would be to decrease rather than to increase the absolute tick size so that the tick-to-price ratio falls. By contrast, MID executions for NASDAQ and small caps are positively related to the stock price, or negatively related to the tick-to-price ratio. Our empirical results therefore suggest that while a reduction in the tick size will be associated with less QJ, it may result in an increase in MID executions at least for some stocks.

An important caveat is that while we find that a reduction of the tick-to-price ratio reduces QJ, this is not necessarily a good policy objective. First, we find no empirical evidence to suggest that QJ is associated with worse market quality in the sample. Furthermore, empirical studies by Werner, Wen, Rindi, Consonni and Buti (WWRCB, 2015) and O'Hara, Saar and Zhung (2014) find that a reduction in tick-to-price ratio (increase in price for a given tick) is associated with a deterioration of market quality (wider spread and less depth). This suggests that while a lower tick-to-price ratio reduces the incentives for QJ, it also tends to encourage traders to switch from limit orders to market orders. Therefore, while a decrease in the tick size may produce a desirable reduction in QJ using a SPV, it may also be associated

[9]The SEC (2010) concept release (page 72) reads: "There may be greater incentives for broker-dealer internalization in low-priced stocks than in higher priced stocks. In low-priced stocks, the minimum one cent per share pricing increment of Rule 612 of Regulation NMS is much larger on a percentage basis than it is in higher-priced stocks. For example, a one cent spread in a $20 stock is 5 basis points, while a one cent spread in a $2 stock is 50 basis points – 10 times as wide on a percentage basis. Does the larger percentage spread in low-priced stocks lead to greater internalization by OTC market makers or more trading volume in dark pools? If so, why? Should the Commission consider reducing the minimum pricing increment in Rule 612 for lower priced stocks?"

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with a decrease in PLB liquidity provision, resulting in wider spreads and less depth.

Our model shows that traders with valuations close to the average valuation among traders are more likely to QJ. In other words, traders that QJ tend not to have strong views on the value of the security being either very high or very low. Instead, they trade opportunistically in the SPV to capture small deviations of price from the average valuation. These trader characteristics fit the description of many HFT traders, and we therefore explore the relationshp between HFT and QJ and MID respectively. We find that our proxy of HFT activity on lit markets is inversely related to both QJ and MID, suggesting a possible substitution effect between transparent and opaque venues.

The paper is organized as follows. In Section 2 we discuss the related literature and in Section 3 we lay out the model and the resulting testable hypotheses. In Section 4 we describe the dataset; in Section 5 we investigate the factors that affect SPT; and in Section 6 we show the effects of SPT on market quality. We conclude in Section 8.

3.2 Related Literature

As SPT takes place on dark venues, our paper is related to the empirical literature on dark pools. Ready (2013) investigates the determinants of dark trading by considering monthly volume by stock for the period June 2005 to September 2007 in two dark pools, Liquidnet and ITG POSIT, that executed approximately 1% of total market consolidated volume. He finds that dark pools execute most of their volume in stocks with low spread and high share volume. Considering that both Liquidnet and ITG POSIT execute at the mid-quote of the primary market spread, Ready's results are comparable (and consistent) with our findings for mid-crossing which show that the effect of depth on MID is positive and that of spread is negative.

Our results are also consistent with Buti, Rindi and Werner (BRW, 2011) who examine a unique dataset for the calendar year 2009 on dark pool activity for a large cross section of U.S. securities. BRW find that liquid stocks are those characterized by more intense dark pool activity. They also find that dark pool volumes increase for stocks with narrow quoted spreads and high inside bid depths, suggesting that a higher degree of competition in the PLB enhances dark pool activity. BRW also investigate the effect of dark trading on market quality and show that increased dark pool activity improves spreads, depth, and short-term volatility. Hatheway, Kwan and Zheng (HKZ, 2013) also study the effects of dark trading on market quality, even though they only focus on effective spread. HKZ look at a sample of NASDAQ

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and NYSE stocks during the period January-March 2011 and find a positive relation between dark pool market share and effective spread. They explain this result with the effects of SPT that should drive uninformed traders away from the lit markets into dark pools thus increasing adverse selection costs on lit markets. We cannot directly compare HKZ' results with ours because they consider dark pool activity as a whole and do not distinguish between dark trading and SPT when looking at the effects on market quality. However, by controlling for endogeneity we find that SPT does not harm spread and depth at the top of the lit market which does not seem consistent with the conjectured cream skimming effect.

International evidence on dark trading and market quality is presented in Degryse, de Jong and van Kerviel (2014) who consider a sample of 52 Dutch stocks and analyze both internalized trades and trades sent to dark pools. They find that when these two sources of dark liquidity are combined, the overall effect on global liquidity is detrimental. Foley and Putnins (2015) and Comerton-Forde, Malinova, and Park (2015) study the introduction of a trade-at rule in Canada which effectively prohibited SPT. Their evidence suggests that SPT in dark venues using QJ results in improved market quality, but that trading in MID crossing networks are not associated with improvements in market quality. Foley and Putnins (2014) find similar evidence based on a natural experiment in Australia.

Our paper is also related to Kwan, Masulis and McInish (2013) who study the effects of competition for order flow on the fragmentation of U.S. equity markets and point out the relevance of SPT, and in particular of QJ, in the distribution of market shares across lit and dark venues. More precisely, they consider NASDAQ and NYSE stocks and show that when the price of a stock crosses the $1 threshold, volume in dark venues increases while volume in traditional exchanges decreases. Finally, Bartlett and McCrary (2013) find both a significant increase in the fraction of offers submitted as subpenny orders below the $1.00 cut-off and a positive effect on market quality.

On the theory side, our paper is related to the models that study how limit order books work.[10] As SPT crucially depends on the tick size and the state of the book -measured by depth and spread- to deliver testable empirical hypotheses the model must have discrete prices. Moreover, the model's equilibrium prices cannot be derived under the assumption of steady state which would inevitably imply a constant state of the PLB.[11] To satisfy these requirements and explicitly analyze QJ, we therefore extend Parlour (1998) and draw our main empirical hypotheses from

[10]To mention but a few, see Buti and Rindi (2013), Goettler, Parlour and Rajan (2005), and Parlour (1998).

[11]See, e.g., Foucault (1999), Foucault, Kadan and Kandel (2005), and Rosu (2009).

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the resulting framework. The framework we build here departs from Werner, Wen, Rindi, Consonni and Buti (WWRCB, 2015) who consider the effects of a reduction in the tick size of a single limit order book on market quality and welfare. Here instead we model competition between a two limit order books, a PLB and a SPV, with different tick sizes. Our framework also differs from Buti, Rindi and Werner (2015) in which a public limit order book competes with a dark pool that executes at the mid-quote of the PLB.

3.3 Model and Empirical Hypotheses

We draw our main empirical hypotheses from a theoretical framework that extends Parlour (1998) to model competition between a PLB and a SPV. In what follows we describe the design of both the PLB and the SPV. We first consider the PLB (our benchmark model) in which traders can only post orders to a standard limit order book. We then compare this model with the extended framework in which a subset of traders - broker-dealers (BDs) - are allowed either to submit orders to the PLB, or to undercut limit orders posted at the top of the PLB by submitting orders in sub-penny increments to the SPV. As discussed in the introduction, Rule 612 prohibits market operators from accepting, ranking, or displaying sub-penny orders. However, as evidenced by the recent SEC allegation, sub-penny orders have been used in dark pools during the 2008-2011 period. Moreover, the Rule makes exceptions for price improvements offered by BDs, and these affect the incentives to submit orders to the PLB in the same way as a formal SPV. Hence, for tractability, we model the ability for BDs to undercut the PLB as a SPV. We derive our empirical hypotheses by investigating how the state of the PLB affects BDs' decisions whether to submit future orders to the SPV or the PLB and how this affects the choice of traders without access to the SPV - regular traders (RTs) - between submitting limit orders to the PLB or opting for market orders. We also study the effects that the SPV trading option has on the market quality of the PLB as reflected in spreads and depth.

3.3.1 Public Limit Order Book

The PLB works like a double auction market that enforces time and price priority and runs over a trading day divided into 4 periods of time, $t = \{t_1, t_2, t_3, t_4\}$. At each period t a risk neutral trader arrives and can submit an order of size 1 to buy or to sell an asset with average value equal to v. Each trader comes to the market with a private value, $\beta\nu$, where β is drawn from the uniform distribution with support

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$U(0,2)$. A non aggressive trader has a β close to 1 while an eager one has values of β close to either 0 (seller) or 2 (buyer).

Upon arrival in period t, the trader observes the state of the book, which is characterized by the number of shares available at each level of the price grid (Table 25), and includes the following possible prices: $A_1 = v + \frac{\tau}{2}, A_2 = v + \frac{3}{2}\tau$, and $B_1 = v - \frac{\tau}{2}$, $B_2 = v - \frac{3}{2}\tau$. The difference between two adjacent prices -the minimum price increment- is the tick size which we set equal to a constant value $\tau_{PLB} = \tau$, and which also corresponds to the minimum inside spread. We define as $S_t = [Q_t^{A_1}, Q_t^{A_2}, Q_t^{B_1}, Q_t^{B_2}]$ the state of the book that specifies the number of shares Q_t available at each price level. A trading crowd provides liquidity at the highest levels of the PLB, and traders are allowed to submit limit orders queuing in front of it. Upon arrival each trader can choose between limit orders $(+1)$ and market orders (-1), and can also choose not to trade.

Market orders are always executed at the best available ask or bid price and their payoff depends on the traders' personal evaluation of the asset, $\beta\nu$. Limit orders' payoff also depends on their execution probability that we indicate by $p_t(A_k|S_t)$ and $p_t(B_k|S_t)$ for a limit sell and for a limit buy order respectively submitted at the ask price A_k, or at the bid price B_k. The payoff are summarized in Table 26. The trader's strategy space at time t is therefore $H_t = \left\{-1^{A_{k\prime}}, +1^{A_k}, 0, +1^{B_k}, -1^{B_{k\prime}}\right\}$, where $+1^{A_k}(-1^{B_{k'}})$ indicates a limit (market) order to sell submitted at the k^{th} level of the book, with $k = 1, 2$, and k' the best available ask price; analogous strategies are available to the trader on the buy side and 0 indicates that the trader decided not to trade.

[Insert Tables 25 and 26 about here]

The state of the PLB evolves according to $S_t = S_{t-1} + h_t$, where S_{t-1} and S_t are respectively the states of the book before and after the trader's order submission and h_t is the change in the PLB induced by the trader's strategy H_t. We assume that when a trader arrives at t_1, the PLB is empty, $S_{t_0} = [0, 0, 0, 0]$. Without loss of generality, in our numerical simulations we assume that the tick size in the PLB is $\tau_{PLB} = 0.1$, and that the price of the asset is $v = 1$.

Figure 6 shows the extensive form of the game. Assume that a trader arriving at the market at t_1 decides to submit a limit sell order at A_2, $H_{t_1} = +1^{A_2}$, so that the state of the book at the end of period t_1 is $S_{t_1} = [1, 0, 0, 0]$. The execution probability of this order depends both on the initial state of the book and on the future orders submitted by the other market participants on both sides of the market. As no shares were standing at A_1 and A_2 before the sell order was submitted, this order

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
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is at the top of the queue on the sell side and would be executed if a market buy order arrives in period t_2, and if this does not happen the order could execute in t_3 or t_4 if no subsequent seller submits an order at A_1. Suppose that the trader arriving at t_2 decides among all strategies shown in Figure 6 to opt for a limit buy order at B_1, $H_{t_2} = +1^{B_1}$; in this case the limit sell order posted at t_1 will not be immediately executed but the probability that it is executed at t_3 is higher compared to the scenario in which the incoming trader at t_2 chooses for example a limit order to sell at A_1, for two reasons. First, if a trader submits a limit sell order at A_1, the limit order initially posted at A_2 would be at the back of the queue, with a smaller execution probability; second, a deep book on the bid side at t_2 implies that the potential buyer in the next period t_3 would be more inclined to post a market rather than a limit order, due to the long queue on the bid side. Suppose now that at t_3 the incoming trader after observing $S_{t_2} = [1, 0, 1, 0]$, decides to gain price priority by submitting a limit sell order at A_1, $H_{t_3} = +1^{A_1}$. In this case, at t_4 the book will open with one share both at the first and at the second price level of the ask side , $S_{t_3} = [1, 1, 1, 0]$, and only the order posted at A_1 will have a positive execution probability. Recall that only one trader arrives at each trading round.

[Insert Figure 6 about here]

The model is solved by backward induction. Because at time t_4 the execution probability of limit orders is zero, traders either submit market orders or decide not to trade. Therefore, traders' equilibrium strategies are:

$$H^*_{t_4}(\beta|S_{t_3}) = \begin{array}{cc} -1^{B_{k\prime}} & \text{if } \beta \in [0,\ \frac{B_{k^{'}}}{v}) \\ 0 & \text{if } \beta \in [\frac{B_{k^{'}}}{v},\ \frac{A_{k^{'}}}{v}) \\ -1^{A_{k\prime}} & \text{if } \beta \in [\frac{A_{k^{'}}}{v}, 2] \end{array} \tag{1}$$

By using these equilibrium strategies together with the distribution of β, we calculate the equilibrium execution probabilities of limit orders submitted at t_3:

$$p^*_{t_3}(A_k|S_{t_3}) = \begin{array}{ll} \int_{\beta\in[\beta:H^*_{t_4}=-1^{A_{k^{'}}}]} \frac{1}{2} d\beta = 1 - \frac{A_{k^{'}}}{2v} & \text{if } A_k = A_{k\prime} \text{ and } Q^{A_k}_{t_2} = 0 \\ 0 & \text{otherwise} \end{array} \tag{2}$$

$$p^*_{t_3}(B_k|S_{t_3}) = \begin{array}{ll} \int_{\beta\in[\beta:H^*_{t_4}=-1^{B_{k^{'}}}]} \frac{1}{2} d\beta = 1 - \frac{B_{k^{'}}}{2v} & \text{if } B_k = B_{k^{'}} \text{ and } Q^{B_k}_{t_2} = 0 \\ 0 & \text{otherwise} \end{array} \tag{3}$$

The execution probabilities of limit orders, $p_{t_3}(A_k|S_{t_3})$ and $p_{t_3}(B_k|S_{t_3})$, are the dynamic link between period t_4 and t_3. Because there is only one period left in the

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trading game, the execution probability of a limit order submitted at t_3 is positive only if the order is posted at the best ask ($A_{k\prime}$) or bid price ($B_{k\prime}$), and if there are no other orders already standing in the book at that price.

A trader arriving at t_3 can choose between a market and a limit order, or decide not to trade. The equilibrium strategies for t_3 depend on the state of the book. As an example, here we discuss the equilibrium strategies for the book opening with room for limit orders on both sides of the market, i.e., $p^*_{t_3}(A_k|S_{t_3}) \neq 0$ and $p^*_{t_3}(B_k|S_{t_3}) \neq 0$.

The trader's optimal strategies are:

$$H^*_{t_3}(\beta|S_{t_2}) = \begin{array}{ll} -1^{B_{k\prime}} & \text{if } \beta \in [0, \beta_{-1^{B_{k\prime}},+1^{A_k},t_3|S_{t_2}}) \\ +1^{A_k} & \text{if } \beta \in [\beta_{-1^{B_{k\prime}},+1^{A_k},t_3|S_{t_2}}, \beta_{+1^{A_k},+1^{B_k},t_3|S_{t_2}}) \\ +1^{B_k} & \text{if } \beta \in [\beta_{+1^{A_k},+1^{B_k},t_3|S_{t_2}}, \beta_{+1^{B_k},-1^{A_{k\prime}},t_3|S_{t_2}}) \\ -1^{A_{k\prime}} & \text{if } \beta \in [\beta_{+1^{B_k},-1^{A_{k\prime}},t_3|S_{t_2}}, 2] \end{array} \tag{4}$$

where

$$\beta_{-1^{B_{k\prime}},+1^{A_k},t_3|S_{t_2}} = \frac{B_{k'}}{v} - \frac{p^*_{t_3}(A_k|S_{t_3})}{1-p^*_{t_3}(A_k|S_{t_3})}\,\frac{A_k - B_{k'}}{v}, \tag{5}$$

$$\beta_{+1^{A_k},+1^{B_k},t_3|S_{t_2}} = \frac{p^*_{t_3}(A_k|S_{t_3})A_k + p^*_{t_3}(B_k|S_{t_3})B_k}{p^*_{t_3}(A_k|S_{t_3}) + p^*_{t_3}(B_k|S_{t_3})}\,\frac{1}{v}, \tag{6}$$

$$\beta_{+1^{B_k},-1^{A_{k'}},t_3|S_{t_2}} = \frac{A_{k'}}{v} + \frac{p^*_{t_3}(B_k|S_{t_3})}{1-p^*_{t_3}(B_k|S_{t_3})}\,\frac{A_{k'} - B_k}{v}. \tag{7}$$

These thresholds are derived by taking into account that the trader arriving at the beginning of period t_3 observes the state of the book S_{t_2}. For instance $\beta_{-1^{B_{k'}},+1^{A_k},t_3|S_{t_2}}$ denotes the threshold between a market sell order hitting the best bid price, $B_{k\prime}$, and a limit sell order posted at the ask price, A_k, and it is derived by equating the payoffs of the two orders. Note that the greater the limit order execution probability, $p^*_{t_3}(A_k|S_{t_3})$, the smaller this threshold and the higher will the probability that traders choose limit rather than market orders be. More generally, if the limit order execution probability at time t is high enough for non-execution costs to be lower than price opportunity costs, the trader will submit a limit order. If instead the execution probability is low, he will choose a market order. This trade-off crucially depends on the value of the tick size and on the price of the stock, v. Specifically, the larger is τ relative to v, the higher is the tick-to-price ratio, and the costlier will the market order be relative to the limit order.

When a trader chooses a limit order, he also has to decide how aggressively to submit this order relative to v. The optimal price at which a trader submits a limit order is also the result of the trade-off between non-execution costs and price opportunity costs: a more aggressive price implies a higher execution probability

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due to both the lower risk of being undercut by incoming traders and the fact that the order becomes more attractive for traders on the opposite side of the market. However, this is obtained at the cost of lower revenue once the order is executed.

From the equilibrium strategies at t_3 we can derive the execution probabilities for limit orders submitted at t_2 and the corresponding equilibrium strategies. The same procedure is then re-iterated to obtain the equilibrium order submission strategies at t_1. Due to the recursive structure of the game, and because traders are indifferent between orders with a zero execution probability, a unique equilibrium always exists.

3.3.2 Sub-Penny Venue

In order to include QJ among the trading strategies of market participants, we extend the benchmark model with only a PLB to include competition from a SPV. All else equal, the SPV has a smaller tick size, $\tau_{SPV} = \frac{\tau}{3}$, and therefore a finer price grid with five levels on both the ask and the bid side, a_l and b_l $(l = 1, .., 5)$, which allows market participants to trade at sub-penny increments (Table 25). We assume that at t_1 the SPV opens empty as the PLB, $S^{SPV}_{t_0} = [0]$. Furthermore, since the SPV is trading against the backdrop of the PLB, we assume that the SPV does not have a trading crowd sitting at a_5 and at b_5.[12]

To add further realism to this new framework, which we label PLB&SPV, we assume that the market is populated by two groups of traders, namely broker-dealers (BDs) and regular traders (RTs), who arrive in each period with probability α and $1 - \alpha$, respectively**,** and that only BDs are allowed to supply liquidity to the SPV.[13] Yet, while only BDs can post limit orders to the SPV, all traders can take advantage of the liquidity offered by both trading platforms and demand liquidity on both the PLB and the SPV. This assumption is consistent with a fast market in which a SOR technology allows all investors to search the best quotes on the consolidated limit order book that includes both the PLB and the SPV. So, as long as the standing orders in the SPV offer better prices than the PLB, all traders, RTs included, can execute against them. Orders posted to the SPV will offer a better price than the PLB when BDs engage in QJ and therefore compete on price against the limit orders posted at the top of the PLB.

As we did for the benchmark framework with only a PLB, we solve the new

[12]This extension differs from WWRCB (2015) in that here we consider two different trading platform that compete with each other for the provision of liquidity, whereas in WWRCB a PLB opens with a large tick size which is subsequently reduced at the second period of the trading game.

[13]The reason why we do not allow all traders to access the SPV is that in real markets retail traders cannot access SPVs. As for the BDs' trading strategies, we also assume that when the BDs' payoffs from trading across the two markets are the same, they submit orders to both markets with equal probability.

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PLB&SPV framework, in which a SPV competes with the PLB, by backward induction starting from t_4, and denote by $A = A_{k'} \bigvee a_{l'}$ and $B = B_{k'} \bigvee b_{l'}$ the best prices across both PLB and SPV. Note that at t_4 the equilibrium strategies of RTs and BDs are the same: both can observe the best available price and, because traders submit only market orders, the BDs can't take advantage of their ability to post liquidity on the SPV. Therefore, the orders' execution probabilities at t_3 do not depend on the type of trader arriving at t_4, hence $p^{*RT}_{t_3}(A_k|S^{PLB}_{t_3}, S^{SPV}_{t_3}) = p^{*BD}_{t_3}(A_k|S^{PLB}_{t_3}, S^{SPV}_{t_3}) = p^{*}_{t_3}(A_k|S^{PLB}_{t_3}, S^{SPV}_{t_3})$.

Consider as an example the case in which at t_3 the PLB opens as $S^{PLB}_{t_2} = [0110]$ and the SPV is empty, $S^{SPV}_{t_2} = [0]$. This case can originate from a limit buy order at B_1 submitted at t_1, $H_{t_1} = +1^{B_1}$, and a limit sell order at A_1 submitted at t_2, $H_{t_2} = +1^{A_1}$.[14] If a RT arrives at t_3, his possible payoffs are:

$$\begin{array}{rcl} H^{RT}_{t_3} = & -1^{B_1} & : \; B_1 - \beta v \\ H^{RT}_{t_3} = & -1^{A_1} & : \; \beta v - A_1 \\ H^{RT}_{t_3} = & 0 & : \; 0 \end{array} \tag{8}$$

and his equilibrium strategies are:

$$H^{*RT}_{t_3}(\beta|[0110],[0]) = \begin{array}{cl} -1^{B_1} & \text{if } \beta \in [0, \beta^{RT}_{-1^{B_1},0,t_3|[0110],[0]}) \\ 0 & \text{if } \beta \in [\beta^{RT}_{-1^{B_1},0,t_3|[0110],[0]}, \beta^{RT}_{0,-1^{A_1},t_3|[0110],[0]}) \\ -1^{A_1} & \text{if } \beta \in [\beta^{RT}_{0,-1^{A_1},t_3|[0110],[0]}, 2) \end{array} \tag{9}$$

By using the optimal β-thresholds associated with these strategies, we compute the execution probability of $H_{t_2} = +1^{A_1}$ conditional on a RT arriving at t_3:

$$\begin{aligned} p^{*RT}_{t_2}(A_1|[0110],[0]) = & \frac{\beta^{RT}_{0,-1^{A_1},t_3|[0110],[0]} - \beta^{RT}_{-1^{B_1},0,t_3|[0110],[0]}}{2} \cdot p^{*}_{t_3}(A_1|[0110],[0]) \\ & + \frac{2 - \beta^{RT}_{0,-1^{A_1},t_3|[0110],[0]}}{2} + \frac{\beta^{RT}_{-1^{B_1},0,t_3|[0110],[0]}}{2} \cdot p^{*}_{t_3}(A_1|[0100],[0]) \end{aligned} \tag{10}$$

If instead a BD arrives at t_3, his possible payoffs are:

$$\begin{array}{rcl} H^{BD}_{t_3} = & -1^{B_1} & : \; B_1 - \beta v \\ H^{BD}_{t_3} = & +1^{a_l} & : \; (a_l - \beta v) \cdot p^{*}_{t_3}(a_l|[0110],[Q^{a_l} = 1]) \\ H^{BD}_{t_3} = & +1^{b_l} & : \; (\beta v - b_l) \cdot p^{*}_{t_3}(b_l|[0110],[Q^{b_l} = 1]) \\ H^{BD}_{t_3} = & -1^{A_1} & : \; \beta v - A_1 \\ H^{BD}_{t_3} = & 0 & : \; 0 \end{array} \tag{11}$$

[14] Another possibility is to have a t_1 a limit sell order at A_1, followed by a limit buy order at B_1.

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where for example $[Q^{a_l} = 1]$ indicates a SPV with one unit at a_l and empty at all other price levels. Both limit and market orders are equilibrium strategies because $p^*_{t_3}(a_l|[0110],[Q^{a_l}=1]) \neq 0$ and $p^*_{t_3}(b_l|[0110],[Q^{b_l}=1]) \neq 0$ for $l = 1, 2$. However, traders need to determine the level of aggressiveness of their limit orders. We consider the bid side as an example: for $H_{t_3} = +1^{b_1}$ to be an equilibrium strategy, $\beta_{+1^{b_1},-1^{A_1},t_3|[0110],[0]} > \beta_{+1^{b_2},-1^{A_1},t_3|[0110],[0]}$. Figure 5 shows that this is always the case for $\frac{\tau}{v} \in (0, 1]$. Because $\beta_{+1^{b_2},+1^{b_1},t_3|[0110],[0]} > \beta_{+1^{a_2},+1^{b_2},t_3|[0110],[0]}$, also $H_{t_3} = +1^{b_2}$ is an optimal strategy. The equilibrium strategies for the BD are:

$$H^{*BD}_{t_3}(\beta|[0110],[0]) = \begin{array}{ll} -1^{B_1} & \text{if } \beta \in [0, \beta^{BD}_{-1^{B_1},+1^{a_1},t_3|[0110],[0]}) \\ +1^{a_1} & \text{if } \beta \in [\beta^{BD}_{-1^{B_1},+1^{a_1},t_3|[0110],[0]}, \beta^{BD}_{+1^{a_1},+1^{a_2},t_3|[0110],[0]}) \\ +1^{a_2} & \text{if } \beta \in [\beta^{BD}_{+1^{a_1},+1^{a_2},t_3|[0110],[0]}, \beta^{BD}_{+1^{a_2},+1^{b_2},t_3|[0110],[0]}) \\ +1^{b_2} & \text{if } \beta \in [\beta^{BD}_{+1^{a_2},+1^{b_2},t_3|[0110],[0]}, \beta^{BD}_{+1^{b_2},+1^{b_1},t_3|[0110],[0]}) \\ +1^{b_1} & \text{if } \beta \in [\beta^{BD}_{+1^{b_2},+1^{b_1},t_3|[0110],[0]}, \beta^{BD}_{+1^{b_1},-1^{A_1},t_3|[0110],[0]}) \\ -1^{A_1} & \text{if } \beta \in [\beta^{BD}_{+1^{b_1},-1^{A_1},t_3|[0110],[0]}, 2) \end{array} \quad (12)$$

It follows that, conditional on a BD arriving at t_3, the execution probability of the limit order posted at A_1 is:

$$\begin{aligned} p^{*BD}_{t_2}(A_1|[0110],[0]) \;=\; & \frac{\beta^{BD}_{+1^{a_2},+1^{b_2},t_3|[0110],[0]} - \beta^{BD}_{+1^{a_1},+1^{a_2},t_3|[0110],[0]}}{2} \cdot p^*_{t_3}(A_1|[0110],[a_2]) \quad (13) \\ & + \frac{\beta^{BD}_{+1^{b_2},+1^{b_1},t_3|[0110],[0]} - \beta^{BD}_{+1^{a_2},+1^{b_2},t_3|[0110],[0]}}{2} \cdot p^*_{t_3}(A_1|[0110],[b_2]) \\ & + \frac{\beta^{BD}_{+1^{b_1},-1^{A_1},t_3|[0110],[0]} - \beta^{BD}_{+1^{b_2},+1^{b_1},t_3|[0110],[0]}}{2} \cdot p^*_{t_3}(A_1|[0110],[b_2]) \\ & + \frac{\beta^{BD}_{-1^{B_1},+1^{a_1},t_3|[0110],[0]}}{2} \cdot p^*_{t_3}(A_1|[0100],[0]) + \frac{2 - \beta^{BD}_{+1^{b_1},-1^{A_1},t_2|[1110],[0]}}{2}. \end{aligned}$$

We compute the total execution probability of the limit order posted at A_1 at t_2 as the weighted average of the two conditional probabilities:

$$p^*_{t_2}(A_1|[0110],[0]) = \alpha p^{BD*}_{t_2}(A_1|[0110],[0]) + (1-\alpha) p^{RT*}_{t_2}(A_1|[0110],[0]) \quad (14)$$

Similarly, we compute the equilibrium strategies for all the other possible states of the book at t_3 and obtain the execution probabilities of the different order types available at t_2. This allows us to derive the equilibrium strategies at t_2. We follow an analogous procedure to solve for the equilibrium order submission strategies at t_1.

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3.3.3 Empirical Hypotheses

We now use this model to draw our main empirical hypotheses on how liquidity of the PLB affects QJ and on how QJ in turn affects market quality. As the PLB opens empty at t_1, we compare two different states of the book at the opening of the second trading period, t_2, which result from the equilibrium order submission strategies of traders arriving at the first period, t_1. So, we exploit the endogenous liquidity generated at t_1 to compare results for liquid and illiquid books at t_2.

3.3.3.1 Factors driving QJ

Consider the order submission strategies of traders in period t_2 with two more periods of the game remaining during which a limit order submitted in t_2 may execute. Figure 7 summarizes how a seller's equilibrium order submission strategies at t_2 translate into order submission probabilities for the different price levels under two scenarios: a liquid book (Liquid PLB) which opens with one share at the best ask A_1 (Panel A), and an illiquid book (Illiquid PLB) which opens with no resting orders, just the trading crowd at A_2 (Panel B). In both cases, we assume that the SPV opens empty.[15] The BDs arrival rate is set to $\alpha = 50\%$, and $\tau = 0.1$ in the numerical example. We report the submission probabilities for both the setup with only the PLB and for the PLB&SPV setup in each panel.

Figure 7 shows that BDs engage more intensively in QJ when competition for the provision of liquidity is strong on the PLB (Panel A), i.e., when there are orders at the top of the book and therefore the quoted half-spread $(A_1 - v)$ is small. Resting orders have time priority, which means that new orders at A_1 would go to the back of the queue. BDs therefore have an incentive to gain price priority by undercutting limit orders posted at the top of the PLB by submitting limit orders on the SPV at a_1. Moreover, as the half-spread is constrained by the tick size, there is no room to post PLB limit orders within the inside spread and there is therefore an additional incentive for traders to undercut existing liquidity via QJ on the SPV. All traders understand these incentives, and that future market orders therefore are more likely to be intercepted by the SPV. As a result, they rationally reduce their own PLB liquidity supply at A_2 compared to when no SPV exists.

When the book opens at t_2 without any depth at the inside (Illiquid PLB) and as before the SPV is also empty, traders still decrease their supply of liquidity to the PLB as in the case of the liquid PLB. However, with an illiquid book undercutting at a_1 is smaller in equilibrium because traders can gain priority over the crowd by

[15] Buyer equilibrium order submission strategies are symmetric.

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simply submitting an order at A_2 which generates a larger surplus.

This leads to our first hypothesis on the factors driving QJ.

[Insert Figure 7 about here]

Hypothesis 1. QJ is higher if the book is liquid, i.e., characterized by high inside depth and/or a narrow inside spread, holding the tick size and the stock price constant.

In our model traders determine whether to submit a market order or a limit order based on the standard trade-off that is related to the tick-to-price ratio. Specifically, the larger is τ relative to v, the higher is the tick-to-price ratio, and the costlier will the market order be relative to the limit orders posted both to the PLB and to the SPV. We solve the model for both $v = 1$ and $v = 1.05$ and therefore compare the results for different relative tick sizes. This leads to our second hypothesis.

Hypothesis 2. QJ is increasing in the tick-to-price ratio: for a given tick size, QJ is decreasing in the stock price.

3.3.3.2 Effects of QJ on market quality.

We now move to the hypotheses on the effects of QJ on the quality of regular exchanges. When traders post limit orders on the SPV to undercut existing liquidity on the PLB, liquidity provision and hence depth and spread on the PLB may deteriorate. However, liquidity demand on the PLB may also decrease. The reason is that, due to the existence of SORs, the better prices available in the SPV intercept market orders away from the PLB. The reduced liquidity demand mitigates the effect of the reduced liquidity supply on the depth and spread on the PLB. Therefore, the effects of QJ on the quality of regular exchanges depend on the relative proportion of limit and market orders that migrate from the PLB to the SPV. The net effect of the reduced supply and demand of liquidity on the quality of the PLB depends on the characteristics of the stock considered; specifically it depends on the liquidity of the book as well as on the price of the stock and therefore on the relative tick size.

Consider first a liquid book. As we showed in Figure 7, Panel A, when the SPV platform is introduced, BDs submit limit orders to the SPV at a_1 in period t_2 to undercut the existing depth at A_1.[16] By comparison, Figure 8 illustrates what happens across all remaining periods and shows that liquidity provision in the SPV (LP_{SPV}) increases. These SPV orders intercept future incoming market orders away from the PLB, and SPV executions (VL_{SPV}) also rise. The effect of BDs' undercutting is that both limit and market orders move from the PLB to the SPV

[16] To economize space we do not present results for the bid side which are symmetric.

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thus reducing both liquidity provision (LP_{PLB}) and volume (VL_{PLB}) on the public venue. The result is that inside depth (DP_{BBO}) increases and spread, both quoted (SP) and relative (RSP), narrow. The reason for why market quality improves in the PLB despite the reduction of the liquidity provision is that when the book is liquid, traders use more market than limit orders and consequently the positive effect of the reduced liquidity demand - which helps preserve the low spread and high depth - prevails. In other words, our model shows that for liquid stocks the main effect of sub-penny trading is to foster price competition. Finally, note that as volume in the PLB decreases significantly, the increase in volume in the SPV is not large enough to compensate for the decline, which means that consolidated volume ($VL_{TOT} = VL_{PLB} + VL_{SPV}$) is smaller in a liquid book with a SPV.

We now turn to the framework with an illiquid opening book (Figure 8). Even for less liquid stocks, when the SPV is introduced both limit and market orders move to the SPV and consequently both liquidity provision (LP_{PLB}) and volume (VL_{PLB}) decline in the PLB. Compared to the liquid case, however, when the book opens illiquid, all else equal, traders tend to use more limit than market orders with the result that more limit than market orders migrate from the PLB to the SPV. As for order flows in the SPV, liquidity provision (LP_{SPV}) and volume (VL_{SPV}) increase but by less than when the book is liquid. Under this scenario with a smaller proportion of market orders migrating to the SPV, the increase in volume in the SPV outweighs the reduction in the PLB and total volume increases.

[Insert Figure 8 about here]

We summarize the results about QJ and market quality in the following hypotheses:

Hypothesis 3. QJ results in a reduction in both the PLB liquidity provision and the PLB volume. SPV volume increases sufficiently for consolidated volume to rise only in the illiquid scenario.

Hypothesis 4. QJ results in improved (worse) depth and spread when the book is liquid (less liquid).

As discussed in the introduction, while several Exchanges have requested that the tick size be lowered to allow sub-penny quoting for all markets, there is at the same time pressure from Congress to raise the tick size for selected stocks following the recommendations in the JOBS Act. This tick-size debate motivates an investigation into how the tick size affects SPT. Because it is the relative tick size that is economically relevant for traders, we compare the model's equilibrium with two different asset values that correspond to different relative tick size. Specifically,

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we compare the case with $v = 1$ and τ=0.1 to the case with a higher price, $v = 1.05$, and the same tick size which results in a smaller relative tick size. As expected, Figure 8 shows that a smaller relative tick size reduces traders' incentive to post limit orders, thus reducing the incentive to post orders to the SPV. Consequently, a smaller relative tick size results in less QJ activity which clearly attenuates all the QJ effects discussed above. This result motivates the following hypotheses.

Hypothesis 5. With a smaller relative tick size QJ decreases and all the effects of QJ are weaker.

We move to empirically testing the model's hypotheses in the next section.

3.4 Data Description

3.4.1 Data and Sample

We construct a sample of stocks stratified by price and market capitalization for both NASDAQ and NYSE. As of December 31, 2009 we identify all common stocks in CRSP which are NYSE or NASDAQ listed. Then we divide all NYSE listed common stocks (i.e., share code 10 or 11) into terciles by market capitalization and price and form nine mutually exclusive groups with the same dimension. From each group we randomly draw 10 stocks for a total of 90 NYSE stocks. We repeat the procedure for NASDAQ stocks using the NYSE breakpoints. This way we create groups of stocks which are comparable across exchanges by market capitalization and price. Our final sample includes the 180 stocks reported in the Online Appendix and spans from October 1 to November 30, 2010, for a total of 42 trading days.

3.4.2 Descriptive Statistics and Definitions

The data we use come from the following sources. Data on number of shares outstanding, market capitalization, closing prices, listing exchanges and share codes are from CRSP. Data for S&P 500 Stock Price Index (SP500) and CBOE S&P 500 Volatility Index (VIX) used to capture market-wide activity are from Federal Reserve of Economic Data (FRED). Our main data source is the TAQ database which we describe in more detail below.

TAQ contains intraday transactions data (trades and quotes) for all securities listed on the NYSE and American Stock Exchange (AMEX), as well as NASDAQ. The TAQ database includes a flag indicating the exchange where the trade was executed or the quote displayed. Each exchange is identified by a symbol/capital letter (except for NASDAQ which has two equivalent symbols, T and Q). The letter

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"D" is used for trades reported to one of the Trade Reporting Facilities (TRFs) and for the NASD Alternative Display Facility (ADF). These facilities record transactions from OTC markets, some transparent non-exchange Electronic Communications Networks (ECNs), broker internalization and dark pools. The crucial information for our analysis is that dark pools trades are reported as "D". The reason is that dark pools do not have to publicly report their quotes and so they do not have to comply with Rule 612 of Reg NMS, which only refers to quoted prices. As a result sub-penny trades executed away from exchanges are reported with the exchange code "D".[17]

We consider only trades and quotes which take place between 9:30:00 AM and 4:00:00 PM. For each day and for each stock we derive the NBBO using the Wharton Research Data Services (WRDS) suggested procedure and we compute the time-weighted bid, ask and total depth, the time-weighted quoted spread in cents and in percentage of the mid-quote, and the intraday price range, defined as (high-low)/high, as a measure of intraday volatility.

We remove erroneous and irregular trades; in particular we keep only trades whose correction indicator is either "00" or "01". We then compute the share volume and (buy) order imbalance defined as the absolute value of ((buys-sells)/share volume) where buys are classified using a modified Lee and Ready (1991) algorithm.[18] Table 27 shows descriptive statistics for our sample of stocks divided by exchange and capitalization.

[Insert Table 27 here]

3.4.3 Price Improvement

In order to identify and classify SPT, we construct an auxiliary variable, the price improvement (PI), which is computed as follows. First, prices are rounded up to the closest cent for sell orders and rounded down to the closest cent for buy orders. Second, PI is obtained as the difference between the rounded price and the reported price. It is always restricted to the interval (0.00, 0.01). Therefore PI is equal to:

$$PI = |rounded(price) - price| \tag{15}$$

To better understand what we are actually measuring in the data in Table 28 we

[17] We can also observe sub-penny trades with other exchange codes. In this case, however, the price improvement is exactly equal to half-cent and is the result of a trade in exchange operated dark pools pricing at the NBBO mid-quote.

[18] We first apply a tick-test considering at most two previous trades. We classify a trade as a buy if its price is above the price of the previous trade (or two trades before); otherwise we classify the trade as a sell. If the trade is still unclassified, we classify it as a buy (sell) if the execution price is above (below) the mid-quote at the time of the trade.

Tesi di dottorato "Essays in Empirical Finance"
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report a sample of a 3 seconds interval of trade for IBM. For convenience we number transactions with a progressive identification number. Furthermore we report the rounded price and the price improvement according to our definition. An example of QJ can be seen on line 19, and an example of MID can be found on line 30. We can also see that, in both cases, the transactions have been executed on exchange D. We are now able to properly define SPT as a function of PI. In particular, we have no SPT when PI is equal to zero and SPT when PI is different from zero.

[Insert Table 28 here]

SPT can be further classified into MID, when PI is exactly equal to half-cent (0.005), and QJ, when PI is strictly positive but different from half-cent.[19] Hence, our rounding procedure is immaterial to the definition of SPT, MID and QJ.

We can use the PI measure to illustrate how large SPT is in the U.S. equity markets. Interpreting PI as the gain from SPT and multiplying it by the number of shares traded in SPT, we obtain the dollar volume captured by stepping ahead of the queue. For example, consider Adobe Systems Inc.: in our sample period the daily average of shares traded is 14.8 million. Of these, 1.62 million are traded in SPT divided between QJ (1.25 million) and MID (0.37 million), which correspond respectively to 8.4% and 2.5% of consolidated share volume. Since QJ and MID effectively lowers the trading costs for active traders, we can compute the average daily gain from SPT for these traders by multiplying PI by the corresponding number of shares traded. For Adobe Systems Inc., active traders gain on average $2,500 from QJ and $1,850 from MID per day. Note that this gain from SPT for active traders corresponds to a loss for passive traders who are being undercut, but this loss is much more difficult to measure.

Figures 9 and 10 report the plot of the average QJ and MID across the sample period for each stock as a function of price, for NASDAQ and NYSE. Graphically we see that on both markets QJ generally decreases with price, while MID increases. Overall the percentage of volume traded in SPT increases when the stock value decreases and seems to be consistent with the fact that a one cent tick size is a binding constraint for low-priced stocks.

[Insert Figures 9-10 here]

[19] Our measure of MID is a lower bound of executions at the mid-quote. The reason is that we are considering as mid-crossing only those executions which result in a sub-penny price. If the spread turns out to be an even multiple of the tick, we will not classify it as MID with our methodology.

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To study the distribution of PIs, in Figures 11 - 12 we group stocks into 10 bins of size 0.001 for two groups of 30 high-priced NASDAQ stocks and 30 high-priced NYSE stocks, separately. For each bin, we report the associated SPT dollar volume as a percentage of the total traded volume; measuring it in share volume or number of trades yields qualitatively the same results. For example, Figure 11 shows that 3.05% of total NASDAQ traded volume is executed with a PI which lies in the interval (0,0.001], while for NYSE it amounts to 2.44%. The most common type of SPT corresponds to PI equal to 0.005. The distribution of PIs decreases almost monotonically as the PI increases, except for the spike at PI exactly equal to half-cent.

[Insert Figures 11-12 here]

3.5 Factors Driving Sub-Penny Trading

To study how SPT varies with market characteristics, and test Hypotheses 1 and 2, we start with daily Fama-MacBeth cross-sectional regressions for both QJ and MID executions. Since MID executions arise both from trading systems using a derivative pricing rule and from undercutting the PLB by exactly half a cent, we expect that the results to be weaker for MID executions. We also note that MID executions are more likely to arise from periodic trading systems such as crossing networks, and this may adversly affect traders willingness to submit MID orders when volatility is high. On the other hand, MID executions may be more likely to arise when order imbalances are high as traders using SPVs become more aggressive facing buying/selling pressure.

We are interested in how QJ and MID are affected by the market conditions as captured by quoted spread and depth and the relative tick size as captured by price. However, we also acknowledge that there may be cross-sectional differences that also affect QJ and MID executions but that are not captured by our model. For example, our model does not have fundamental uncertainty and there is no asymmetric information. The model does not incorporates fees,trading is driven entirely by differences in valuation and we assume that the distribution of valuations is symmetric. A skewed distribution of valuations causes either buying or selling pressure depending on the location of the mean, and a smaller range of valuations symmetric around 1 (e.g. [0.5, 1.5]) implies that traders use fewer market orders. We want to control for the beta distribution in the cross-section when evaluating the effect of our variables of interest. The beta distribution is of course not observable, but we proxy for differences in the beta distributions across stocks by the absolute

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value of the percent order imbalance (to measure buying and selling pressure), the intraday range and volume (to measure the dispersion in valuations). Finally, we acknowledge that there may be structural differences between stocks predominately traded on the NYSE compared to stocks traded on Nasdaq and therefore include a dummy to capture the listing exchange.

Motivated by the discussion above, we use two sets of regressors in the analyses. When testing Hypotesis #1 (the positive relationship between QJ and book liquidity), we include a dummy variable which is equal to one when the stock is NYSE listed, time-weighted cent quoted spreads and log of time-weighted bid depth to measure market conditions, the absolute of order imbalance in percent as a measure of one-sided market, and intraday percent price range as a measure of volatility[20] When testing Hypothesis #2 (the positive relationship between QJ and tick-to-price ratio), we rely on closing price to examine the effect of the relative tick size, log of share volume as a measure of differences of opinion, , the absolute of order imbalance in percent as a measure of one-sided market, and intraday percent price range as a measure of volatility. The average daily estimated coefficients and t-statistics are reported in Tables 29 and 30. The t-statistics are based on the Newey-West adjusted standard errors with 5 lags.

[Insert Tables 29-30 here]

We first examine the cross-sectional relationship between QJ and MID and quoted cent spread and time-weighted depth. The results in Table 29 (Panel A.1) column (1) show that QJ decreases significantly in quoted spread and increases significantly in depth as predicted by Hypothesis #1. The results indicate that a stock with a quoted spread of 5 cents instead of 4 cents (sample mean) has a rate of QJ that is 0.072 percentage points lower, which means QJ goes from 6.59% (sample mean) to 6.52% or a reduction of 1.1%. Similarly, a stock with an average depth that is two times the sample mean of 144.99 round lots has QJ that is 0.3917 percentage points higher than the average firm or an increase of 6.0%. A midcap stock with an average depth of 50 round lots instead of 25 round lots has QJ that is the same 0.3912 percentage points higher than the average midcap stock, or an increase of 7.23% compared to the mean for midcap stocks of 5.49%. The Table also shows that QJ is significantly higher for NASDAQ than NYSE stocks, and QJ is increasing significantly in volatility, and decreasing significantly in order imbalance. The results are robust to subsampling by listing exchange in columns (2) and (3), and market capitalization in columns (4)

[20]We do not include log of share volume in these tests as it is highly correlated with depth which is our main variable of interest.

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and (5). The only exception is that the effect of quoted cent spreads is insignificant for the largest stocks. There is simply not enough cross-sectional dispersion of cent spreads within our sample of large stocks to pin down the coefficient.[21] The results are also robust to estimating Fama Macbeth regressions with quoted cent spread and time-weighted depth separately. [22]. Further, we verify that the results hold when estimating a collapsed version of the Fama-Macbeth with the time-series average QJ regressed on the time-series average quoted cent spread (coefficient is -0.156 with t=-3.94) and time-weighted depth (coefficient is 0.556 with t=3.31) plus control variables.

Table 29 (Panel A.2) reports the same cross-sectional regressions with the frequency of MID executions as the left hand side variable. MID executions decline significantly in the quoted spread. However, while higher depth is associated with more MID executions overall and for NYSE-listed stocks, depth is associated with significantly lower MID executions for Nasdaq stocks and for small caps. Moreover, the amplitude of the estimated coefficients on quoted spread and depth are smaller for the MID regressions. Hence, as expected the effect of market conditions on MID is economically less significant than on QJ. Note also that the significant coefficients on order imbalance and intraday range in the MID regressions are of the opposite sign compared to the QJ regressions. Specicially, MID executions are higher for stocks with lower intraday range and with higher order imbalances. As explained above, this is natural as a significant fraction of MID executions are likely to arise from periodic trading systems using a derivative pricing rule.

We also use the Fama-MacBeth framework to study the effect of the relative tick size on QJ and MID. Since all stocks in the U.S. prices above $1.00 is constant at 1 cent, we use closing price to examine the effect of the relative tick size on QJ. In Table 30 (Panel A.1) column (1) we show that QJ decreases significantly in price. In other words, QJ increases significantly in the relative tick size as predicted by Hypothesis #2. This is true after controlling for listing exchange, share volume, order imbalance and volatility. The results imply that a stock with a price $10 below the sample mean of $29.70 has QJ that is 0.35 (6.94%, compared to the sample mean of 6.59%) percentage points higher which represents a 5.3% increase in QJ. The sign on the remaining coefficient are consistent with our earlier results, and the coefficient on share volume has the same sign as the coefficient on intraday range which is consistent with our conjecture that they both proxy the dispersion in valuations. The results are again robust to subsampling by listing exchange in columns (2) and

[21]The median cent spread for large stocks is 1.07 and the 75th percentile cent spread is 1.54.
[22]Results are available on request.

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(3), with the exception that the sign on order imbalance switches for NYSE stocks but the estimate is not statistically significant. The results are also robust for small cap stocks in column (5). However, for large cap stocks the effect of price is positive but insignificant and the coefficient on order imbalance is positive and significant. In other words, the relative tick size is not a strong driver for QJ in large cap stocks. This result is not surprising when we consider that there are relatively few large cap stocks for which the relative tick size is large (price is low).

Table 30 (Panel A.2) reports the same cross-sectional regressions with the frequency of MID executions as the left hand side variable. MID executions are not significantly affected by the relative tick size in the overall sample, for NYSE-listed stocks, or for large caps. However, for Nasdaq-listed stocks and small caps, a higher relative tick size (lower price) is associated with fewer MID executions. Moreover, while the sign of the coefficients on share volume remain positive and they are significant across the board, the coefficients on order imbalance and intraday range in the MID regressions are again of the opposite sign compared to the QJ regressions and they are mostly statistically significant. Thus, it again appears that MID executions are affected differently by our control variables, and it might be also due to the fact that MID are a mixture of continuous SPVs and periodic derivative pricing systems.

It is important to remember that the empirical evidence discussed above refers to evaluating a reduction in the tick-to-price ratio that arises because of an increase in the stock price, holding the absolute tick size fixed at \$0.01. The motivation for this approach is that there is no variation in the absolute tick size for the vast majority of stocks in the U.S. The question remains how QJ would be affected by a reduction in the absolute tick size from say \$0.01 to \$0.0001. This question could in theory be answered by studying stocks that cross the \$1 threshold discussed above to examine whether there is a significant change in QJ at the threshold. However, unfortunately, Financial Industry Regulatory Authority (FINRA) collects prices with a maximum of four decimal digits thus not allowing researchers to study QJ for stocks priced below \$1.[23]

In sum the multivariate Fama-MacBeth regression analysis shows that QJ is significantly higher for NASDAQ than NYSE stocks, that QJ is negatively related to quoted spread and positively related to depth, and that QJ is positively related to the relative tick size (negatively related to price). These results are consistent with both Hypotheses 1 and 2. By contrast, MID executions are higher for NYSE than

[23]**Informal conversations with U.S. traders informed us that banks are not even aware of the possibility to trade at more than 4 decimals, suggesting that perhaps QJ below \$1 does not even exist.**

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for NASDAQ stocks, and while they are negatively related to quoted spread and positively related to depth, they are only significantly - and in this case negatively - related to the relative tick size for small caps. Hence, while the results for MID executions support Hypothesis 1, they do not support Hypothesis 2.

3.5.1 HFT and QJ

We have documented a significant incidence of QJ in U.S. markets, and have also shown that QJ is more intense when competition among liquidity providers is high, and when the relative tick size is large. However, we have not discussed what type of trader is more likely to engage in QJ. What characteristics would make a trader more prone to QJ? In the model, QJ arises when a trader arrives at the market and would normally have submitted a limit order, but the long queue makes him or her instead QJ. The reason he or she jumps the queue by submitting a sub-penny order is that the execution probability for a limit order submitted to the LOB is low given the long queue and the cost of using a market order too high given the quoted spread. Therefore, a trader that engages in QJ is likely to have a valuation that is not extreme in the support of the ß distribution. It follows that if we were to add traders who do not have strong views on the value of the security, but that trade opportunistically, we would see more QJ. These characteristics describe a type of trader that has become increasingly active in securities markets, a High Frequency Trader (Hagstromer and Norden, 2013). This insight begs the question if the incidence of QJ is increasing because of the growth in HFT trading? In other words, is it primarily HFT traders jump ahead of existing orders on the LOB? To answer this question, we study the relationship between HFT and QJ. Following Angel, Harris and Spatt (2010, 2013) we compute the ratio between quote updates on lit markets and consolidated number of trades as our empirical proxy for HFT. This way we should capture HFTs that affect quotes, in other words only the lit market trading by potential HFTs. Note that quotes are not available for dark trading so we cannot define a similar measure for SPV trading. However, to the extent that HFT on the lit market is strongly correlated with HFT in SPVs, we should be able to use our proxy for lit- market HFT to proxy for the relationship between HFT and QJ.

[Insert Tables 29-30 here]

In Table 29 (Panel B.1), we add our proxy for HFT to the specification in Table 29 (Panel A.1) and in Table 30 (Panel B.2) we add our proxy for HFT to the specification we estimated in Table 30 (Panel A.2). We include all control

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variables from Panel A in each Table, and the estimated coefficients are virtually unchanged. In both cases, we find that our proxy for HFT is negatively related to both QJ and MID for the overall sample and for all the subsamples. The only exception is small caps in Table 30 (Panel B.1) where the estimated relationship is positive but insignificant. For the overall sample, a stock with a 49 quote updates per trade compared to the sample mean of 24.5 quote updates per trade has QJ that is 0.22-0.29 percentage points lower than the mean, or 6.37%-6.30%, instead of 6.59% (sample mean). The effect is considerably stronger for NASDAQ listed stocks and Large stocks. For example, a Large stock with 24.5 quote updates per trade more than the average Large stock has QJ that is 2.03-2.72 percentage points lower than the mean of 7.68%.

Recall that our HFT proxy only captures trading by HFTs in lit markets. Therefore, if lit market HFT and HFT in SPVs are complements (positively correlated), our results suggest that there is no evidence indicating that HFTs are responsible for the increasing incidence of QJ. On the contrary, our results suggest that HFT trading is actually neatively correlated with QJ. It is of course possible that HFT in SPVs is instead a substitute for HFT trading in the lit market. If this is the case, then HFT in the lit market would be negatively correlated with HFT in SPVs. Under this assumption, our finding of a negative relationship between lit market HFT and QJ implies that QJ is indeed positively correlated with HFT using dark venues. Unfortunately, without a better proxy for HFT in SPVs, we cannot conclusively determine whether HFT in lit markets is a substitute or a complement for HFT in SPVs.[24]

3.6 Sub-Penny Trading and Market Quality

We now move to test our hypotheses on the effects of SPT, on the market quality of regular exchanges. The issue is that PLB market quality and dark trading are jointly determined as pointed out in BRW (2011), so to establish a causal relationship we have to address the endogeneity issue.

To deal with the inherent endogeneity of SPT and market quality, we need to find good instruments for SPT and market quality, respectively. In a recent paper studying the impact of low latency trading on market quality, Hasbrouck and Saar (2013) propose using low latency trading in other stocks during the same time period as an instrument for low latency trading in a particular stock. We follow their

[24]Yao and Ye (2015) find that a HFT proxy based on quote updates relative to trades and a version of the strategic run measure proposed by Hasbrouck and Saar (2013) are negatively correlated, high-lighting the difficulty of estimating HFT activity based on TAQ data.

Tesi di dottorato "Essays in Empirical Finance"
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suggestion and use SPT for other stocks (not i) on day t as an instrument for SPT in stock i. Because we have observed that there are systematic differences between exchanges and across market capitalization groups in SPT, we refine their instrument slightly. We require that the other stocks (not i) are listed on the same exchange as stock i and that their market capitalization is in the same market capitalization group as stock i. The market quality measures we use are the time-weighted percent quoted spread and the logarithm time-weighted bid-depth. We estimate a two-equation simultaneous model for SPT, which can be either QJ or MID, and market quality measures (MQMs) using both traditional 2SLS and a two step generalized method of moments (GMM) procedure. Specifically, we estimate the following two-equation simultaneous model for each MQM:

$$\begin{aligned} MQM_{i,t} &= a_1 SP_{i,t} + a_2 MQM_{NOTi,t} + \varepsilon_{1,t} \\ SP_{i,t} &= b_1 MQM_{i,t} + b_2 SP_{NOTi,t} + \varepsilon_{2,t} \end{aligned} \tag{16}$$

As instruments for $SP_{i,t}$, we use $SP_{NOTi,t}$, which is the average SPT of other stocks listed on the same exchange, in the same market capitalization group. Note that we exclude stock i. Similarly, as an instrument for $MQM_{i,t}$, we use $MQM_{NOTi,t}$, which is the average market quality measure for other stocks listed on the same exchange, in the same market capitalization group. We again exclude stock i. This estimation method is chosen to address the endogeneity of SPT and MQM and obtain a consistent estimate of the a_1 coefficient that tells us how SPT affects market quality.

We estimate the above system of equations for all stocks and days in a panel. To control for stock fixed effects, we de-mean all variables by deducting the in-sample average and divide the de-meaned variables by their in-sample standard deviation. As a result, the estimated coefficients can be interpreted as the response to a one standard deviation shock. We do not include any trend in the system nor do we de-trend our variables since the visual inspection of the data tells us that the variables are stationary in the sample period. We estimate system (16) using a 2SLS procedure; standard errors are double clustered by stock and day.[25] We consider four measures of market quality, time-weighted bid depth to proxy for depth, share volume, time-weighted quoted cent spread, and the time-weighted relative spread.[26]

Tables 31 and 32 report the results from the simultaneous equation model for the

[25]We repeat the estimation using a GMM approach allowing for heteroskedasticity of unknown form, still double clustering standard errors. The results are nearly identical.

[26]Results for depth defined as the average of bid depth plus ask depth are virtually identical.

Tesi di dottorato "Essays in Empirical Finance"
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relationship between QJ and MID and the four market quality measures (bid depth, share volume, quoted spread and relative spread). The results for share volume will be discussed separately in the next sub-section as the left hand side variables are different. We are primarily interested in the a_1 and b_1 coefficients: a_1 measures the effect of SPT on market quality and b_1 measures the effect of market quality on SPT. The coefficients on our instruments, a_2 and b_2 , are positive and highly significant. In other words, they appear to be good instruments. We present the results for the whole sample in column (1) and for small and large capitalization stocks separately in columns (2) and (3). We rely on market capitalization to proxy for stock liquiity.

Results for the factors driving QJ (b_1) continue to be consistent with Hypothesis #1 even after we attempt to control for endogeneity: QJ is positively related to the liquidity of the book. Specifically, Table 31 (Panel A.1) shows that b_1 is positive and statistically significant for depth, while Table 32 (Panel A.1 and B.1) shows that it is negative and statistically significant for quoted and relative spread respectively. The magnitude of the effects are large. A one standard deviation increase in QJ results in a 0.28 standard deviation increase in depth, a 0.19 standard deviation reduction in quoted cent spreads, and a 0.27 standard deviation decrease in relative basis point spreads. Similarly, MID is significantly positively related to the liquidity of the book once we take endogeneity into account. Consistent with our previous results, the magnitude of the effects are smaller and it is only singificant for the overall sample for depth and quoted spread.

Tables 31 and 32 show that QJ has a positive effect on market quality. The coefficient a_1 is positive and statistically significant in the depth system in Table 31 (Panel A.1) and negative and statistically significant in both the quoted cent spread and the relative basis point spread system Tables 32 (Panel A.1 and B.1). Recall that variables are standardized, so a one standard deviation increase in QJ results in a 0.34 standard deviation increase in quoted depth. Similarly, a one standard deviation increase in QJ resutls in a decrease in quoted cent spread of 0.31 standard deviations and a decrease in relative basis point spreads of 0.49 standard deviations. These are again economically sizable effects.

Interpreting market capitalization as a rough proxy of liquidity, we study the results for large and small capitalization stocks separately in columns (2) and (3) of each table. Consistently with Hypothesis 4, the results show that for stocks with liquid books (large caps) an increase in QJ is associated with an improvement of market quality measured by depth and spreads . By contrast, the relationship is not significant for stocks with less liquid books (small caps).

We report the relationship between MID and our market quality measures taking

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di CONSONNI FRANCESCO
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endogeneity into account in Tables 31 and 32. Recall that the effect of market quality measures on MID is captured by the coefficients b_1. The results for depth (Table 31, Panel A.2); quoted spread; and relative spread (Table 32, Panels A.2 and B.2) are similar, albeith statistically slightly weaker, than they are for QJ. Interestingly, we do not observe any significant effect of MID on depth, quoted or relative spread (a_1). In other words, MID executions do not appear to significantly affect market quality in our sample.

A similar difference between QJ and MID is documented by Comerton-Forde, Malinova, and Park (2015) and Foley and Putnins (2015) for Canadian stocks. They find that when the Canadian securities regulator started enforcing a trade-at-rule (essentially imposing a minimum price variation of one penny for all platforms) in October 2012, dark trading decreased signficantly and the result was a deterioration of market quality measures such a quoted and effective spreads and price efficiency measures such as autocorrelation, variance ratio, and delay. The authors pin down the source of the deterioration in market quality to the reduction in dark trading using platforms that offer two-sided liquidity and we label QJ. By contrast, the change in mid-crossings in the Canadia market following the introduction of the trade-at-rule has no statistically significant effect on market quality measures such as quote spread and market efficiency.

In our model, we have no asymmetric information, but we expect informed traders to choose the venue that offers the best liquidity supply, be it a PLB, a SPV, or even a CN executing at the midpoint of the PLB. We conjecture that if we added a new competing venue that executes at the midquote of the PLB to our model, the CN would attract more aggresive traders than the SPV. Hence, we conjecture that the difference in the results for QJ compared to MID can be attributed to other elements possibly associated with HFT access or trading fees.

An important caveat is therefore that we do not control for make-take fees. In practice, traders use dark markets to trade at sub-penny not only to step ahead of exiting limit orders at the top of regular exchanges but sometimes also to save on take fees to the extent that fees are lower in sub-penny venues. By internalizing orders a broker-dealer avoids paying the fees imposed by lit venues. Therefore, one should take the effects of different possible make-take fee structures into account both to correctly interpret our results, and to appropriately discuss our policy implications.We cannot take into account make-take fees into account as for trades marked with the code “D” we cannot distinguish among different trading venues that all report with code “D”.

[Insert Tables 31-32 here]

Tesi di dottorato "Essays in Empirical Finance"
di CONSONNI FRANCESCO
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3.6.1 Volume

Our model also has predictions about how QJ affects volume. Hypothesis #3 states that consolidated volume should decrease in QJ for liquid books, but increase in QJ for illiquid books. We therefore also study the relationship between consolidated volume and QJ using 2SLS and a two-step GMM procedure. We estimate a two-equation simultaneous model for SPT, which can be either QJ or MID, and volume (VOL) using both traditional 2SLS and a two-step generalized method of moments (GMM) procedure. For this analysis, we measure both QJ and MID in shares (as opposed to relative to consolidated volume) in order to more closely match the empirical tests to the model. Specifically, we estimate the following two-equation simultaneous model for each VOL:

$$\begin{aligned} VOL_{i,t} &= a_1 SP_{i,t} + a_2 VOL_{NOTi,t} + \varepsilon_{1,t} \\ SP_{i,t} &= b_1 VOL_{i,t} + b_2 SP_{NOTi,t} + \varepsilon_{2,t} \end{aligned}$$

As instruments for $SP_{i,t}$, we use $SP_{NOTi,t}$, which is the average SPT of other stocks listed on the same exchange, in the same market capitalization group. Note that we exclude stock i. Similarly, as an instrument for $VOL_{i,t}$, we use $VOL_{NOTi,t}$, which is the average consolidated volume for other stocks listed on the same exchange, in the same market capitalization group. We again exclude stock i. This estimation method is chosen to address the endogeneity of SPT and VOL and obtain a consistent estimate of the a_1 coefficient that tells us how SPT affects market quality.

The results in Table 31, Panel B.1, show that as predicted by Hypothesis 3 there is a positive and significant effect of share volume on QJ (b_1), and a negative but not statistically significant effect of QJ on consolidated volume (a_1) in the overall sample.Columns (2) and (3) show that this conclusion is not affected by dividing the sample by market capitalization.

By contrast, in Table **32**, Panel B.2, we do find a significantly negative effect of MID executions on consolidated volume (a_1) for the overall sample. Recall that MID executions have a no significant effect on depth and spreads. Therefore,we conclude once again that while QJ is associated with improved market quality and lower consolidated volume, we find no significant effects of MID on either market quality or consolidated volume.

3.6.2 Robustness Check

We rerun our simultaneous equation models including additional controls which are exogenous and can affect both market quality and SPT. In particular, following again

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Hasbrouck and Saar (2013), we include the daily return on SP500 and its volatility (proxied by VIX) to take into account market-wide activity. The same concern has been addressed by Brogaard, Hendershott and Riordan (2013) when studying the relation between HFT and volatility. Specifically, we estimate the following system of equations, which is a modification of system (16):

$$\begin{aligned} MQM_{i,t} &= a_1 SP_{i,t} + a_2 MQM_{NOTi,t} + a_3 SP500_t + a_4 VIX_t + \varepsilon_{1,t} \\ SP_{i,t} &= b_1 MQM_{i,t} + b_2 SP_{NOTi,t} + b_3 SP500_t + b_4 VIX_t + \varepsilon_{2,t} \end{aligned} \quad (17)$$

We present the results in Tables 33 and 34. All our results are robust to the inclusion of the additional controls.

In unreported results, we also find that our results are generally robust to rerunning the analysis of the relationship between SPT and share volume in Section 6.1 using the measures of SPT that are normalized by consolidated volume. The only difference compared to the results reported above is that MID (normalized by consolidated volume) is significantly associated with lower share volume for small cap stocks.

3.7 Conclusions and Policy Implications

During the last decade financial markets have been characterized by the growth of dark markets and fast trading. These two elements have fostered the development of sub-penny trading (SPT) which is a particular form of dark trading. SPT takes place when traders take advantage of the Sub-Penny Rule (Rule 612) and its exceptions by executing orders in the dark market or internalizing customers' orders at fractions of the tick size. In this way they gain price priority over the orders sitting at the inside quotes of regulated markets. Sub-penny orders are then executed against traders who demand liquidity by using smart order routing programs that allow them to hit the best quotes available both in lit and in dark markets.

In this paper we show that in the U.S. approximately 10% of share volume executes at sub-penny increments). Approximately 3% executes exactly at the mid-quote, and could be the result either of QJ or of a midpoint cross (MID) in an opaque venue. These volumes are rapidly increasing and SPT is a concern to regulators as it can reduce the incentive for liquidity providers to post limit orders on regular exchanges and hence worsen market depth. For this reason in 2010 the SEC proposed the Trade-At Rule to curtail dark trading, and more recently such rule has

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been introduced in Canada (October 2012) and in Australia (May 2013).[27] In the 2010 concept release on market microstructure the SEC also opened the debate on SPT by asking questions on the factors that drive SPT, the effects of SPT on the quality of lit markets and more precisely on the adequate policy instrument to use to influence SPT. In this paper we answer most of these questions and to draw our empirical hypotheses we build a model of competition between a Public Limit Order Book and a Sub-Penny Venue.

We find that SPT varies significantly by listing exchange, as QJ is significantly higher for NASDAQ than for NYSE listed stocks. Consistently with our model's predictions, we show that QJ is positively related to depth and negatively related to quoted cent and relative basis point spreads, and to stock price. This means that broker-dealers use dark markets for QJ especially for stocks where competition for the provision of liquidity is high and hence it is difficult to gain price priority on lit platforms. The use of QJ is also intense in low-priced stocks for which the profit from price improvement is higher relative to the asset value.

As predicted by our model, we find that QJ improves both depth and quoted cent and relative basis point spreads, especially for large capitalization stocks. Also as predicted by our model, QJ is associated with lower share volume, but this relationship is not statistically significant. By contrast, we find no relationship between MID and market quality and MID is significantly negatively related to share volume. In sum, we do not find any evidence supporting that SPT harms liquidity. We also build a proxy of HFT as the ratio between quotes updates on lit markets and consolidated number of trades and find that QJ is negatively related to lit market HFT, suggesting that they could be strategic substitutes in traders' order submission decisions. If an increase in QJ is associated with both a reduction in HFT and an improvement in PLB market quality, it might well be that the improvement in market quality is also due to HFTs migrating from the PLB to the SPV. Therefore it would be interesting to investigate whether all market participants (HFTs and non-HFTs), both in the PLB and in the SPV benefit from the existence of QJ. We leave this interesting topic for future research.

[27] On October 12, 2012 the Investment Industry Regulatory Organization of Canada introduced a Trade-At Rule that now gives lit orders priority over dark orders in the same venue. In particular small dark orders under 5,000 shares or C$100,000 dollars in value must offer at least half a tick in price improvement for stocks that have a one tick spread, and a full tick of price improvement for stocks with higher spreads. Following the implementation of this rule, the Canadian dark share of volume dropped by more than 50% (Rosenblatt Securities Inc., February 2013). Even the Australian Securities and Investments Commission on May 26, 2013 adopted a new regulation for dark venues aimed at containing dark trading for transactions of size smaller than blocks. The key component of the new regulatory regime is the adoption of a minimum size threshold for dark orders.

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Table 25: **Price Grid**
This Table shows the price grid for both the Public Limit Order Book (PLB) and the Sub-Penny Venue (SPV). v is the asset value and τ is the tick size.

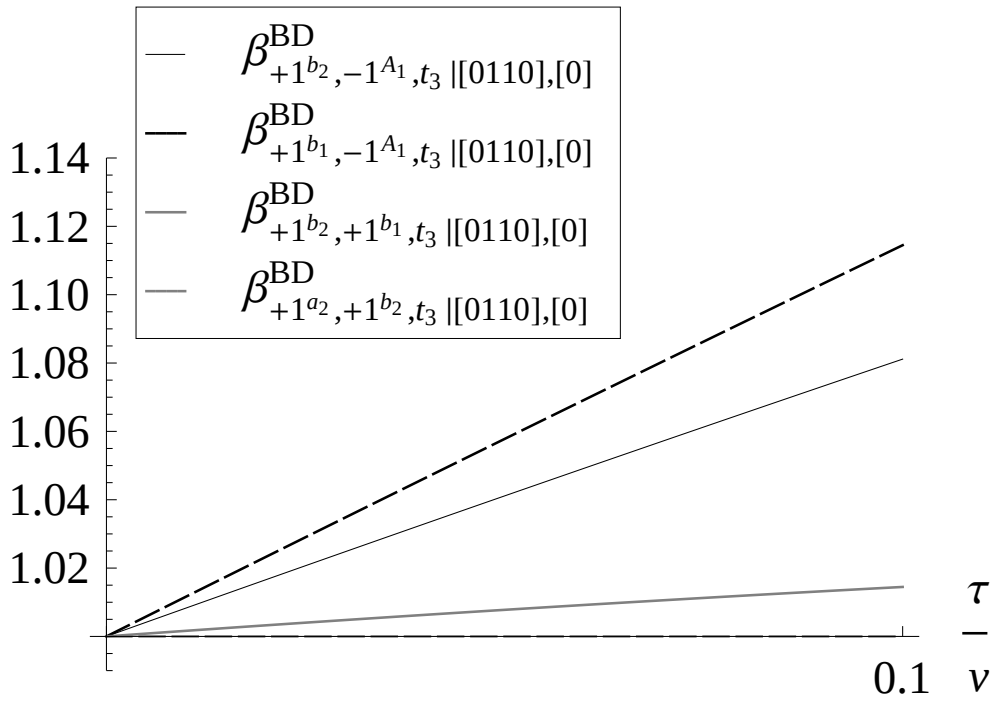
PLB	Price	SPV
A_2	$v + \frac{9}{6}\tau$	a_5
	$v + \frac{7}{6}\tau$	a_4
	$v + \frac{5}{6}\tau$	a_3
A_1	$v + \frac{3}{6}\tau$	a_2
	$v + \frac{1}{6}\tau$	a_1
	$v - \frac{1}{6}\tau$	b_1
B_1	$v - \frac{3}{6}\tau$	b_2
	$v - \frac{5}{6}\tau$	b_3
	$v - \frac{7}{6}\tau$	b_4
B_2	$v - \frac{9}{6}\tau$	b_5

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Table 26: **Order Submission Strategy Space.**
This Table reports in column 3 the payoffs, $U(\cdot)$, of the order strategies H_t listed in column 1. In the case of market orders, $A_{k'}$ and $B_{k'}$ always refer to the best ask and bid prices.

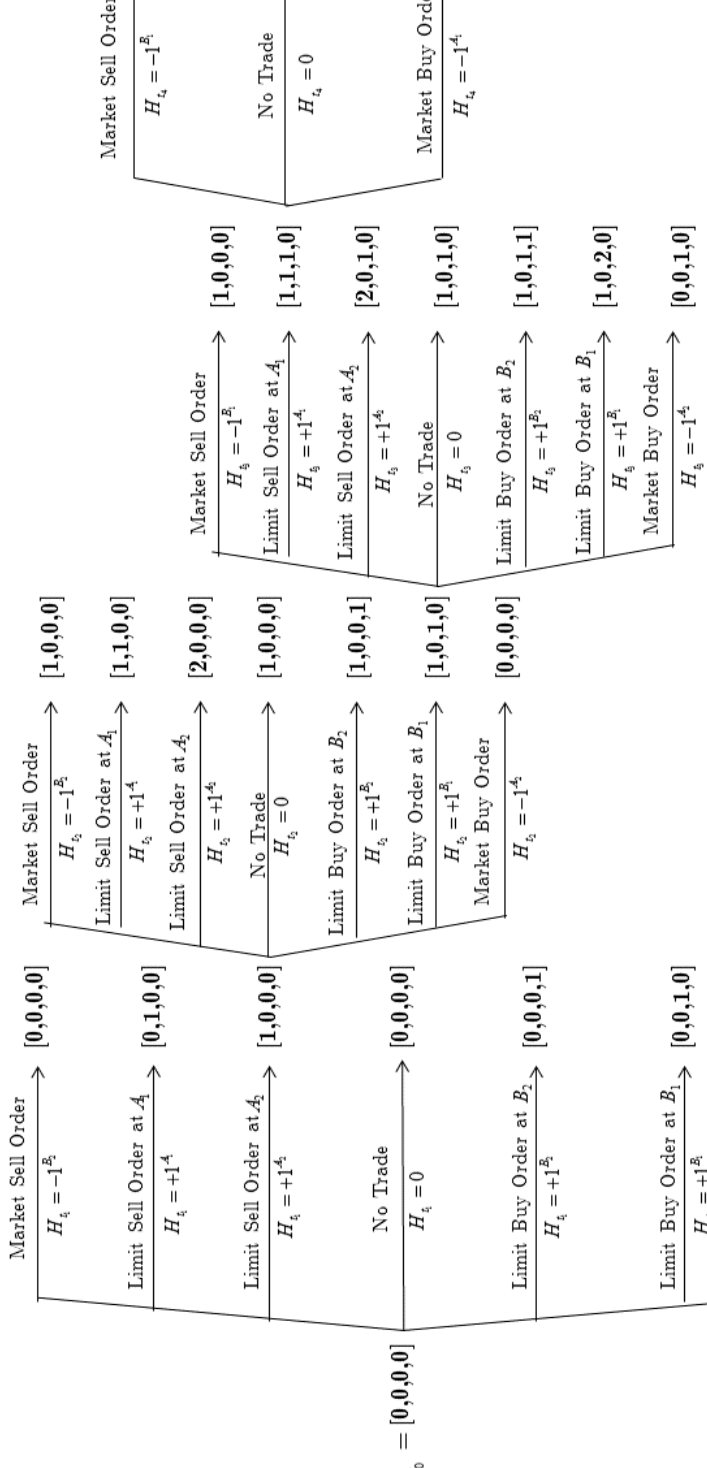
Strategy	H_t	$U(\cdot)$
Market Sell Order	$-1^{B_{k'}}$	$B_{k'} - \beta v$
Limit Sell Order	1^{A_k}	$p_t(A_k \mid S_t)(A_k - \beta v)$
No Trade	0	0
Limit Buy Order	1^{B_k}	$p_t(B_k \mid S_t)(\beta v - B_k)$
Market Buy Order	$-1^{A_{k'}}$	$\beta v - A_{k'}$

Figure 5: **Broker Dealers' β-thresholds.** This Figure shows the BDs' β-thresholds at t_3, for $S_{t_1} = [0110]$ and $SPV_{t_1} = [0]$. The thresholds are computed for $\tau = 0.1$ and $\alpha = 50\%$.



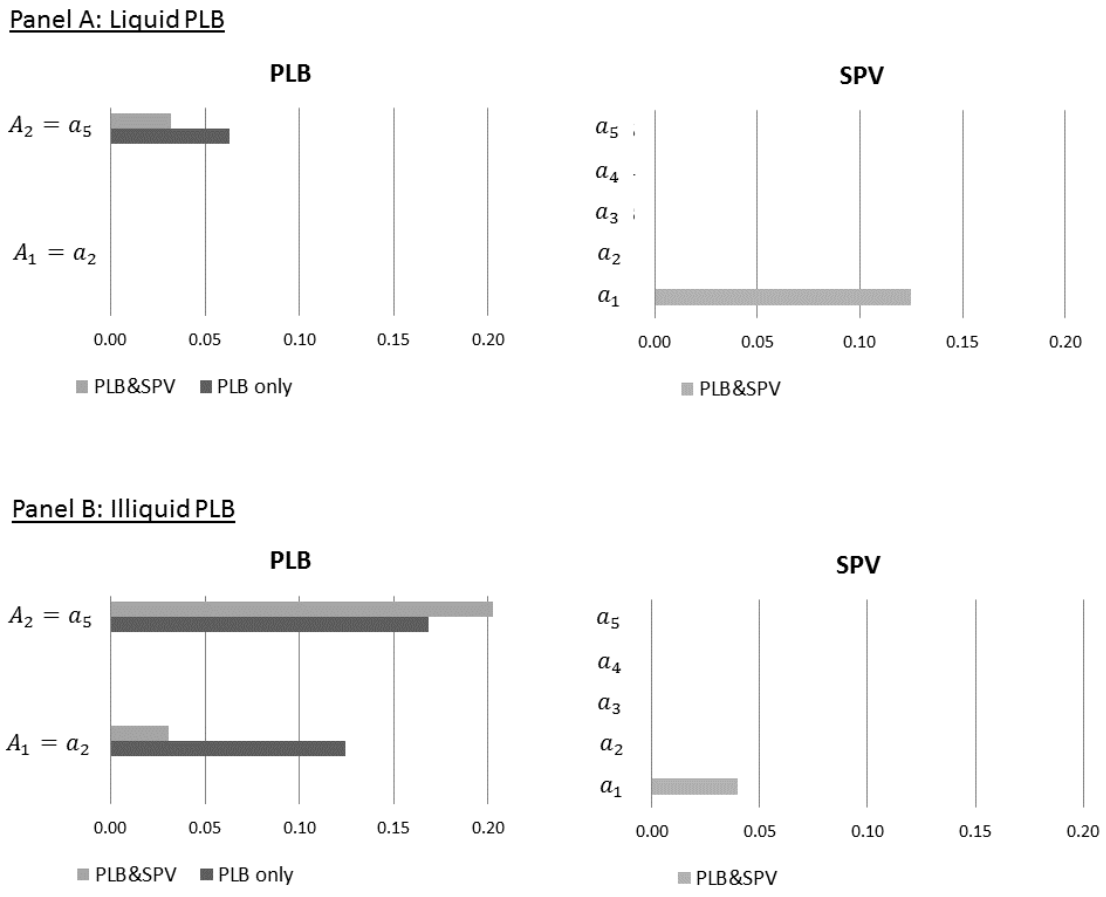
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Figure 6: **Public Limit Order Book**
Example from the extensive form of the game in the framework with a Public Limit Order Book only. The book opens empty at t_1: $S_{t_0} = [0, 0, 0, 0]$. H_t refers to the strategy of the trader who arrives at the market in period t. All available H_t are defined in Table 26.



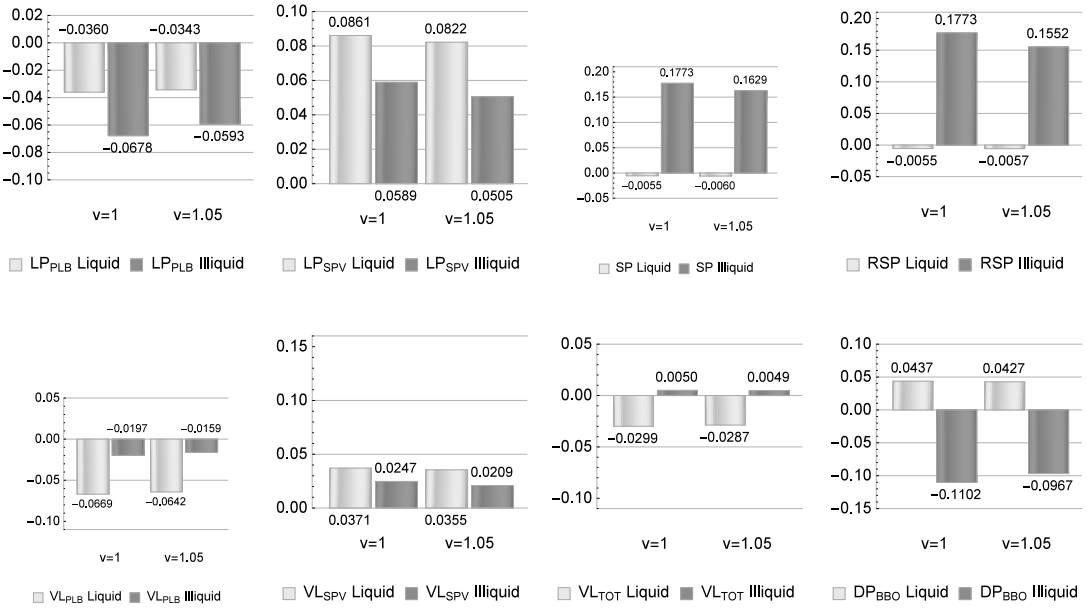
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Figure 7: **Trading Strategies at t_2**
This Figure reports the equilibrium submission probabilities at t_2 of limit orders posted on the ask side under two equilibrium opening states of the Public Limit Order Book (PLB) at t_2, "Liquid PLB" (Panel A) and "Illiquid PLB" (Panel B), that differ for the number of shares at the first level of the ask side of the book, $S_{t_1} = [0, 1, 0, 0]$, and $S_{t_1} = [0, 0, 0, 0]$, respectively. We denote by "PLB ONLY" the framework with only a PLB with tick size $\tau_{PLB} = \tau$, and price grid $\{A_1, A_2\}$, and with "PLB&SPV" the framework with both a PLB and a Sub-Penny Venue (SPV) with tick size $\tau_{SPV} = \frac{\tau}{3}$, and price grid $\{a_1, a_2, a_3, a_4, a_5\}$. Results are computed assuming broker-dealers' arrival rate $\alpha = 50\%$, and $\tau = 0.1$.



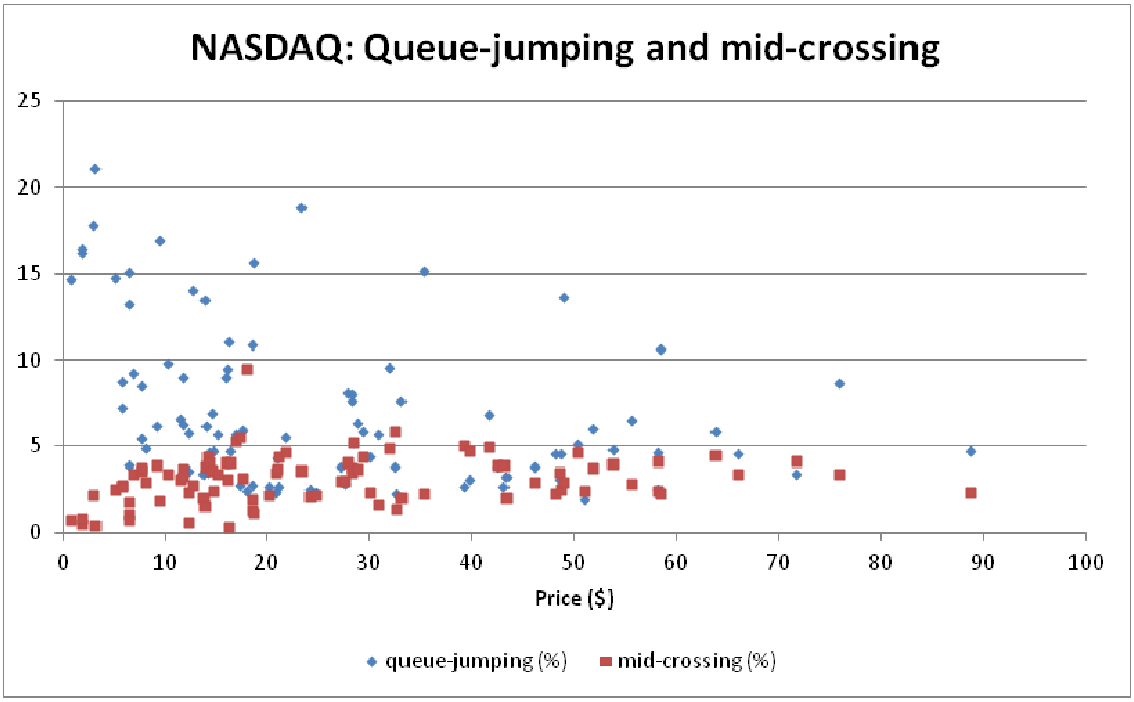
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Figure 8: **Order Flows and Market Quality**
This Figure reports statistics for order flows and market quality that result from the comparison between the benchmark framework with only a Public Limit Order Book (PLB) with tick size $\tau_{PLB} = \tau$, and the extended model (PLB&SPV) in which a PLB with the same tick size as the benchmark model competes with a Sub-Penny Venue (SPV) characterized by a smaller tick size, $\tau_{SPV} = \frac{\tau}{3}$. We consider two equilibrium opening states of the PLB at t_2, "Liquid" and "Illiquid", that differ for the number of shares at the first level of the ask side of the book, $S_{t_1} = [0, 1, 0, 0]$, and $S_{t_1} = [0, 0, 0, 0]$, respectively. For order flows, this panel reports statistics on liquidity provision and trading volume both for the PLB (LP_{PLB} and VL_{PLB}) and for the SPV (LP_{SPV} and VL_{SPV}). We also provide total trading volume (VL_{TOT}=VL_{PLB}+VL_{SPV}). For market quality, we report statistics on depth at the best bid-offer (DP_{BBO}), absolute and relative spread (SP and RSP). The statistics are computed as the average difference between the value of the measure in the framework in which the PLB competes with the SPV, and the value of the same statistic in the benchmark framework with only a PLB: $\Delta y = \frac{1}{k}\sum_{t=t_2}^{t_k}[y_t^{PLB\&SPV} - y_t^{PLB\ only}]$, where $y = \{DP_{BBO}, SP, RSP, VL_{PLB}, LP_{PLB}, VL_{SPV}, LP_{SPV}, VL_{TOT}\}$, $k = 2$ for $\{DP_{BBO}, SP, RSP, LP_{PLB}, LP_{SPV}\}$, and $k = 3$ for $\{VL_{PLB}, VL_{SVP}, VL_{TOT}\}$. We present results for a broker-dealers' arrival rate $\alpha = 50\%$,$\tau = 0.1$, and $v = \{1, 1.05\}$.



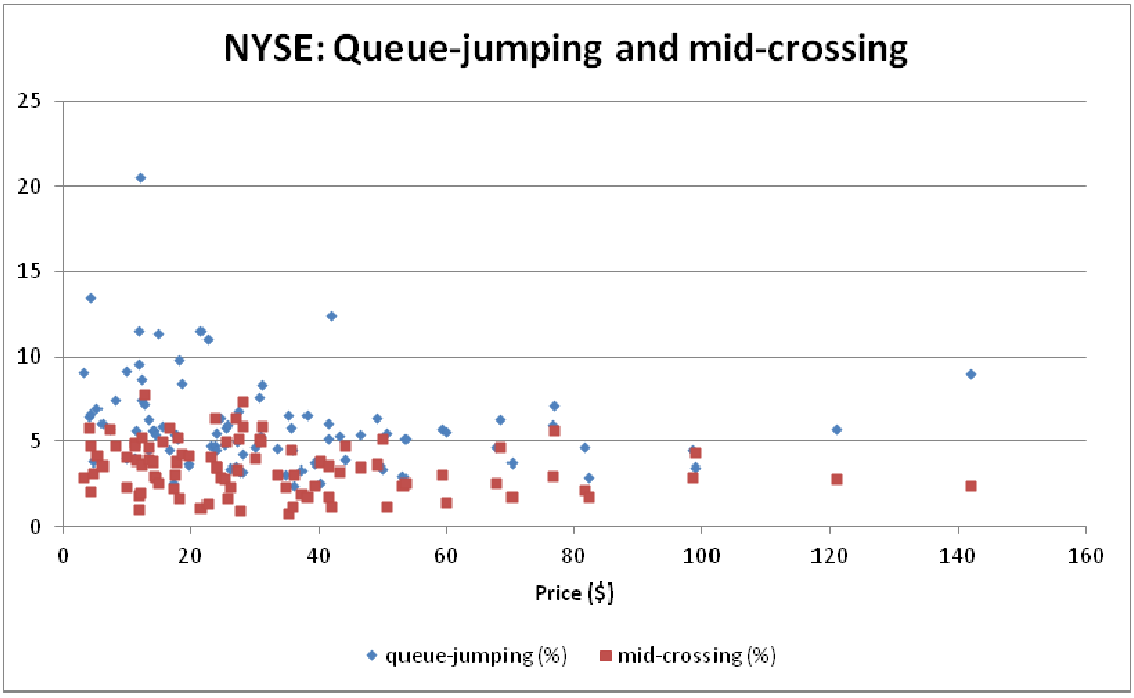
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Figure 9: **NASDAQ queue-jumping and mid-crossing versus stock price**
This figure reports the queue-jumping and mid-crossing percentage over the sample period for each NASDAQ stock against the price of the stock.



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Figure 10: **NYSE queue-jumping and mid-crossing versus stock price**
This figure reports the queue-jumping and mid-crossing percentage over the sample period for each NYSE stock against the price of the stock.



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Figure 11: **NASDAQ distribution of Sub-Penny (including mid-crossing)**
This figure reports the Sub-Penny in percentage of consolidated volume for each bin over the sample period and for the group of 30 high-priced NASDAQ stocks.



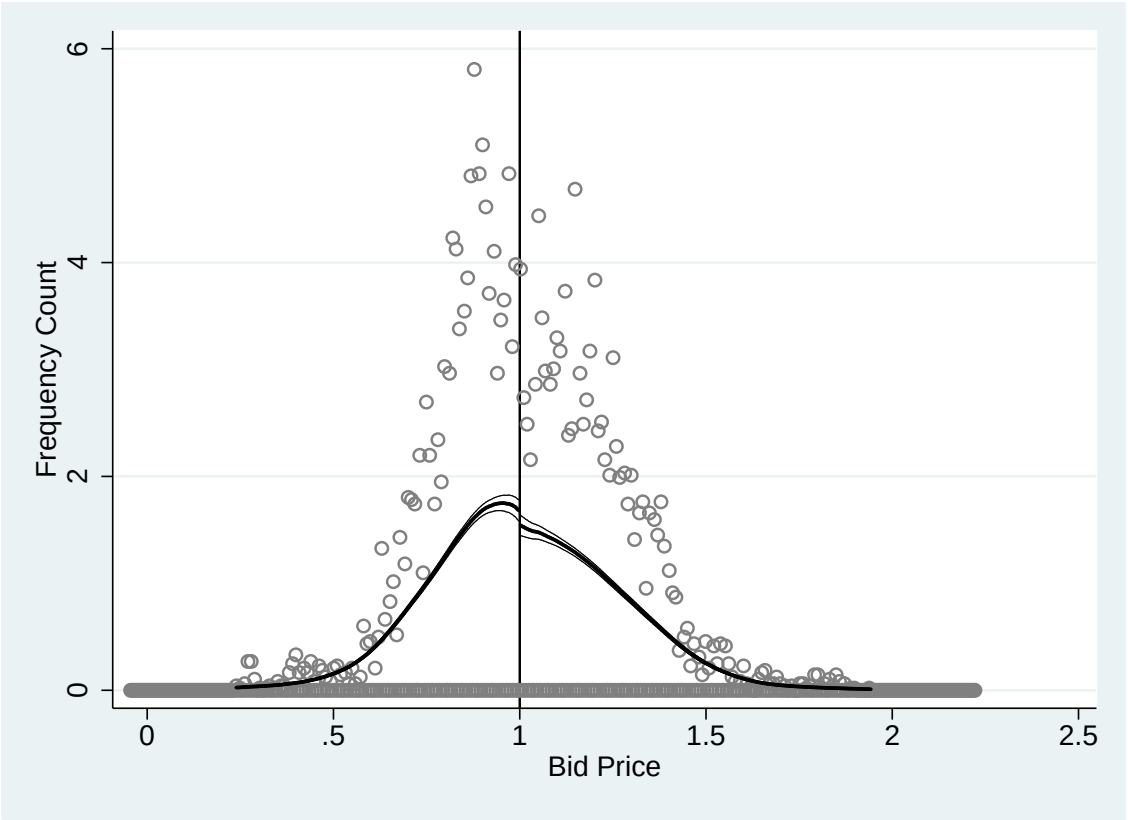
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Figure 12: **NYSE distribution of Sub-Penny (including mid-crossing)**
This figure reports the Sub-Penny in percentage of consolidated volume for each bin over the sample period and for the group of 30 high-priced NYSE stocks.



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Figure 13: **Density Representation for bid price**
This figure reports the density of the assignment variable (i.e., bid price) to assess the continuity of the variable itself across the cutoff. The points represent the smoothed histogram while the solid black line represents the smoothed density with confidence bands (solid grey lines). Both histogram and density are smoothed using a triangle kernel.



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Table 27: **Stocks descriptive statistics**
The sample period is October 1, 2010 - November 30, 2010. All variables are daily (time-weighted) averages. Market cap is the stock's market capitalization in millions from CRSP. Closing price is in dollar from CRSP. Relative spread is the difference between the bid and ask price over the midquote. Quoted spread is the difference between the bid and ask price (cents $). Price range is the difference between the maximum and the minimum price over the maximum price. Share volume is the number of shares traded in millions. Bid depth is the bid depth at NBBO in unit of trade (100 shares). Queue-jumping is the QJ on D computed as the ratio of volume executed in QJ over the total consolidated volume. Mid-crossing is the MID on D computed as the ratio of volume executed in MID over the total consolidated volume. Sub-Penny is the SPT on D computed as the ratio of volume executed in SPT over the total consolidated volume. Statistics are reported for the full sample (NASDAQ and NYSE) and for the NASDAQ and the NYSE separately. Furthermore, for each panel, we report the summary statistics for the three market capitalization groups (SMALL, MEDIUM and LARGE). The first five variables are in Panel A of the table, while the other five are in the Panel B of the table

			Panel A			
	Market Cap (Million $)	Closing Price ($)	Time-weighted relative spread ($^{0}/_{000}$)	Time-weighted quoted spread (cents $)	Price range (%)	HFT Proxy
NASDAQ+NYSE	**7,324.30**	**29.70**	**0.149**	**3.96**	**0.04**	**24.5**
Small	534.48	26.78	0.272	6.53	0.05	40.5
Medium	1740.48	29.10	0.112	3.92	0.03	25.0
Large	19,697.94	33.22	0.062	1.43	0.02	7.89
NASDAQ	**5,807.27**	**26.58**	**0.153**	**3.18**	**0.03**	**17.2**
Small	462.41	22.75	0.287	4.64	0.04	25.4
Medium	1,648.04	26.92	0.111	3.30	0.03	18.8
Large	15,311.36	30.05	0.061	1.41	0.02	6.4
NYSE	**8,841.33**	**32.83**	**0.145**	**4.74**	**0.04**	**31.7**
Small	606.55	30.81	0.257	8.85	0.05	59.0
Medium	1,832.93	31.28	0.114	4.46	0.03	30.5
Large	24,084.53	36.40	0.064	1.46	0.02	9.2

			Panel B		
	Share Volume (M)	Time-weighted bid depth (UoT)	Queue-jumping on D (%)	Mid-crossing on D (%)	Sub-Penny on D (%)
NASDAQ+NYSE	**5.92**	**144.99**	**6.59**	**3.34**	**9.93**
Small	0.41	9.58	7.68	2.51	10.19
Medium	1.77	23.22	5.49	3.40	8.89
Large	15.61	399.17	6.61	4.10	10.71
NASDAQ	**3.69**	**37.67**	**7.16**	**3.16**	**10.32**
Small	0.55	14.39	9.11	2.11	11.23
Medium	2.32	27.01	5.79	3.51	9.30
Large	8.61	71.59	6.57	3.86	10.43
NYSE	**8.15**	**250.31**	**6.03**	**3.51**	**9.54**
Small	0.23	4.76	6.25	2.90	9.15
Medium	1.28	19,43	5.18	3.29	8.48
Large	22.16	726.73	6.65	4.35	11.00

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Table 28: **Price improvement calculation**
In this table we report an example of price improvement calculation and sub-penny identification according to our definition. We report a 3 seconds interval of transactions for IBM on date 10/01/2010.

ID	Symbol	Date	Time	Exchange	Price	Size	Rounded Price	Price Improvement	Type of Sub-Penny
1	IBM	20101001	10:00:00	K	135,76	100	135,76	0	None
2	IBM	20101001	10:00:00	K	135,77	100	135,77	0	None
3	IBM	20101001	10:00:00	K	135,84	100	135,84	0	None
4	IBM	20101001	10:00:00	N	135,75	100	135,75	0	None
5	IBM	20101001	10:00:00	N	135,77	100	135,77	0	None
6	IBM	20101001	10:00:00	N	135,78	400	135,78	0	None
7	IBM	20101001	10:00:00	N	135,8	600	135,8	0	None
8	IBM	20101001	10:00:00	N	135,84	779	135,84	0	None
9	IBM	20101001	10:00:00	P	135,73	100	135,73	0	None
10	IBM	20101001	10:00:00	P	135,75	100	135,75	0	None
11	IBM	20101001	10:00:00	P	135,84	400	135,84	0	None
12	IBM	20101001	10:00:00	T	135,73	200	135,73	0	None
13	IBM	20101001	10:00:00	T	135,75	100	135,75	0	None
14	IBM	20101001	10:00:00	T	135,77	300	135,77	0	None
15	IBM	20101001	10:00:00	T	135,8	2039	135,8	0	None
16	IBM	20101001	10:00:00	T	135,81	100	135,81	0	None
17	IBM	20101001	10:00:00	T	135,84	200	135,84	0	None
18	IBM	20101001	10:00:01	D	135,64	196	135,64	0	None
19	**IBM**	**20101001**	**10:00:01**	**D**	**135,7375**	**200**	**135,74**	**0,0025**	**Queue-Jumping**
20	IBM	20101001	10:00:01	N	135,67	100	135,67	0	None
21	IBM	20101001	10:00:01	N	135,69	100	135,69	0	None
22	IBM	20101001	10:00:01	N	135,72	100	135,72	0	None
23	IBM	20101001	10:00:01	N	135,73	600	135,73	0	None
24	IBM	20101001	10:00:01	N	135,74	200	135,74	0	None
25	IBM	20101001	10:00:01	P	135,71	100	135,71	0	None
26	IBM	20101001	10:00:01	Z	135,74	200	135,74	0	None
27	IBM	20101001	10:00:02	P	135,69	100	135,69	0	None
28	IBM	20101001	10:00:03	B	135,76	100	135,76	0	None
29	IBM	20101001	10:00:03	D	135,76	100	135,76	0	None
30	**IBM**	**20101001**	**10:00:03**	**D**	**135,825**	**300**	**135,83**	**0,005**	**Mid-Crossing**
31	IBM	20101001	10:00:03	J	135,76	100	135,76	0	None
32	IBM	20101001	10:00:03	K	135,75	200	135,75	0	None
33	IBM	20101001	10:00:03	K	135,76	200	135,76	0	None
34	IBM	20101001	10:00:03	N	135,71	100	135,71	0	None
35	IBM	20101001	10:00:03	N	135,73	100	135,73	0	None
36	IBM	20101001	10:00:03	N	135,74	300	135,74	0	None
37	IBM	20101001	10:00:03	N	135,75	200	135,75	0	None
38	IBM	20101001	10:00:03	N	135,76	500	135,76	0	None
39	IBM	20101001	10:00:03	N	135,77	100	135,77	0	None
40	IBM	20101001	10:00:03	N	135,78	200	135,78	0	None
41	IBM	20101001	10:00:03	N	135,79	200	135,79	0	None
42	IBM	20101001	10:00:03	N	135,8	300	135,8	0	None
43	IBM	20101001	10:00:03	N	135,81	100	135,81	0	None
44	IBM	20101001	10:00:03	N	135,82	100	135,82	0	None
45	IBM	20101001	10:00:03	N	135,83	400	135,83	0	None
46	IBM	20101001	10:00:03	P	135,76	200	135,76	0	None
47	IBM	20101001	10:00:03	P	135,77	200	135,77	0	None
48	IBM	20101001	10:00:03	T	135,75	400	135,75	0	None
49	IBM	20101001	10:00:03	T	135,76	800	135,76	0	None
50	IBM	20101001	10:00:03	T	135,77	200	135,77	0	None
51	IBM	20101001	10:00:03	T	135,81	600	135,81	0	None
52	IBM	20101001	10:00:03	T	135,83	300	135,83	0	None
53	IBM	20101001	10:00:03	Z	135,76	200	135,76	0	None
54	IBM	20101001	10:00:03	Z	135,77	100	135,77	0	None
55	IBM	20101001	10:00:03	Z	135,81	400	135,81	0	None

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Table 29: **Queue-jumping and Mid-crossing: Spread and Depth**

This table reports the results of regressions of queue-jumping and mid-crossing, separately, on contemporaneous market characteristics based on daily cross-sectional Fama-MacBeth regressions. Queue-jumping is 100 times daily queue-jumping dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). Mid-crossing is 100 times daily mid-crossing dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). We take the log of depth. Dollar spreads are multiplied by 100. The relative order imbalance is the absolute value of (buys-sells)/share volume. The intraday price range is defined as (high-low)/high. NYSE is a dummy variable which takes the value of 1 for stocks whose primary listing exchange is NYSE. HFT proxy is the ratio between quotes updates on lit markets and consolidated number of trades. Panel A reports the results for the baseline specification, while Panel B reports the results including the HFT proxy along with the same controls. We report the average daily coefficients on top and t-statistics below, computed according to Newey-West with 5 lags. The symbols ***, ** and * indicate statistical signicance at the 0.1%, 1%, and 5% levels, respectively.

Panel A: Queue-jumping and Mid-crossing: Spread and Depth

	A.1: Queue-jumping					A.2: Mid-crossing				
	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
	All	NYSE	NASDAQ	Large Cap	Small Cap	All	NYSE	NASDAQ	Large Cap	Small Cap
NYSE	-0.933***			0.171**	-1.894***	0.440***			0.489***	0.571**
	(-15.47)			(3.00)	(-15.97)	(5.05)			(7.23)	(3.02)
quoted spread cents (TAQ)	-0.072***	-0.032***	-0.107***	0.111	-0.060***	-0.024***	-0.014**	-0.086***	-0.174	-0.017*
	(-8.74)	(-5.18)	(-6.47)	(1.47)	(-4.44)	(-4.65)	(-2.70)	(-6.23)	(-1.42)	(-2.39)
time-weighted depth (TAQ)	0.573***	0.376***	0.758***	0.328***	2.012***	0.126***	0.323***	-0.128***	0.035	-0.209***
	(23.35)	(16.86)	(16.07)	(12.12)	(19.92)	(4.50)	(7.80)	(-4.10)	(0.67)	(-4.43)
order imbalance (TAQ)	-2.269***	0.694	-4.503***	3.955***	-5.160***	2.132***	1.912**	2.490***	-0.345	2.405**
	(-4.01)	(1.19)	(-6.08)	(5.62)	(-4.72)	(4.29)	(2.92)	(4.07)	(-0.84)	(2.72)
(high-low)/high (TAQ)	45.530***	7.480*	103.564***	18.574*	34.903***	-7.711***	-3.905	-16.776***	-0.229	1.089
	(5.59)	(2.13)	(13.91)	(2.41)	(4.74)	(-4.38)	(-1.46)	(-9.44)	(-0.05)	(0.40)
Constant	2.488***	3.369***	-0.244	2.488***	-3.617***	2.239***	1.232***	4.448***	3.879***	3.350***
	(8.16)	(18.30)	(-0.58)	(8.69)	(-7.34)	(11.71)	(3.73)	(16.50)	(6.56)	(9.54)
Observations	7,560	3,780	3,780	2,520	2,520	7,560	3,780	3,780	2,520	2,520
R^2	0.12	0.08	0.23	0.11	0.27	0.12	0.08	0.23	0.11	0.27

Panel B: Queue-jumping and Mid-crossing: Spread, Depth and HFT

	B.1: Queue-jumping					B.2: Mid-crossing				
HFT proxy	-0.009***	-0.003	-0.042***	-0.111***	-0.010**	-0.019***	-0.014***	-0.048***	-0.132***	-0.017***
	(-3.92)	(-1.21)	(-6.29)	(-3.97)	(-3.40)	(-7.11)	(-7.33)	(-6.04)	(-6.51)	(-5.12)
Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Observations	7,560	3,780	3,780	2,520	2,520	7,560	3,780	3,780	2,520	2,520
R^2	0.13	0.10	0.24	0.14	0.28	0.07	0.10	0.11	0.13	0.12

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Table 30: **Queue-jumping and Mid-crossing: Price**

This table reports the results of regressions of queue-jumping and mid-crossing, separately, on contemporaneous market characteristics based on daily cross-sectional Fama-MacBeth regressions. Queue-jumping is 100 times daily queue-jumping dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). Mid-crossing is 100 times daily mid-crossing dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). We take the log of share volume. Closing price is the price at the end of the day. The relative order imbalance is the absolute value of (buys-sells)/share volume. The intraday price range is defined as (high-low)/high. NYSE is a dummy variable which takes the value of 1 for stocks whose primary listing exchange is NYSE. HFT proxy is the ratio between quotes updates on lit markets and consolidated number of trades. Panel A reports the results for the baseline specification, while Panel B reports the results including the HFT proxy along with the same controls. We report the average daily coefficients on top and t-statistics below, computed according to Newey-West with 5 lags. The symbols ***, ** and * indicate statistical signicance at the 0.1%, 1%, and 5% levels, respectively.

Panel A: Queue-jumping and Mid-crossing: Price

	A.1: Queue-jumping					A.2: Mid-crossing				
	(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
	All	NYSE	NASDAQ	Large Cap	Small Cap	All	NYSE	NASDAQ	Large Cap	Small Cap
NYSE	-0.890***			0.149*	-2.101***	0.437***			0.533***	0.836***
	(-15.818)			(2.321)	(-12.553)	(5.221)			(8.329)	(4.087)
share volume (TAQ)	0.276***	0.245***	0.241***	0.446***	1.065***	0.374***	0.418***	0.361***	0.225***	0.534***
	(9.258)	(6.288)	(8.791)	(9.603)	(16.167)	(11.163)	(9.234)	(14.101)	(4.749)	(8.601)
closing price (TAQ)	-0.035***	-0.016***	-0.064***	0.002	-0.078***	0.003	-0.005	0.020***	-0.002	0.014***
	(-19.189)	(-8.022)	(-21.819)	(0.762)	(-15.201)	(1.841)	(-1.968)	(5.852)	(-0.761)	(4.858)
order imbalance (TAQ)	-1.424*	0.747	-3.146***	2.177*	-5.744***	0.442	-0.160	0.795	-1.340**	2.076*
	(-2.347)	(1.069)	(-4.421)	(2.349)	(-4.908)	(0.743)	(-0.163)	(1.364)	(-2.851)	(2.227)
(high-low)/high (TAQ)	33.050***	3.864	84.015***	18.129*	30.855***	-4.772**	-0.978	-9.393***	-4.236	-3.049
	(4.714)	(1.003)	(13.422)	(2.247)	(6.891)	(-3.168)	(-0.418)	(-3.962)	(-0.951)	(-1.193)
Constant	2.262***	1.953**	2.281**	-3.270***	-7.251***	-3.644***	-3.761***	-3.776***	-0.194	-7.089***
	(3.578)	(2.801)	(3.502)	(-3.628)	(-6.021)	(-6.049)	(-4.819)	(-7.333)	(-0.201)	(-6.572)
Observations	7,560	3,780	3,780	2,520	2,520	7,560	3,780	3,780	2,520	2,520
R^2	0.11	0.08	0.22	0.12	0.25	0.08	0.11	0.12	0.10	0.11

Panel B: Queue-jumping and Mid-crossing: Price and HFT

	B.1: Queue-jumping					B.2: Mid-crossing				
HFT proxy	-0.012***	-0.001	-0.058***	-0.083***	0.002	-0.009***	-0.006**	-0.022***	-0.104***	-0.008**
	(-4.053)	(-0.414)	(-8.947)	(-4.011)	(0.594)	(-3.851)	(-3.364)	(-5.068)	(-5.009)	(-2.938)
Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Observations	7,560	3,780	3,780	2,520	2,520	7,560	3,780	3,780	2,520	2,520
R^2	0.12	0.09	0.24	0.14	0.26	0.09	0.12	0.13	0.13	0.13

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Table 31: **Queue-jumping and Mid-crossing: Depth and Share Volume**

This table reports the results from the analysis of the relation between queue-jumping and mid-crossing activity and time-weighted bid depth (Panel A) and share volume (Panel B). We measure queue-jumping activity as QJ, which is defined as 100 times daily queue-jumping dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). We measure mid-crossing activity as MID, which is defined as 100 times daily mid-crossing dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). When analyzing the relation between QJ (or MID) and share volume, we use gross measure (i.e., not normalized to total consolidated volume). Due to the potential simultaneity between time-weighted bid depth (log of) and share volume (log of), respectively, and queue-jumping and mid-crossing activity, we estimate the following two-equation simultaneous model for SP, which can be either QJ or MID, and MQM, which can be either time-weighted bid depth or share volume :

$MQM_{i,t} = a_1 QJ_{i,t} + a_2 MQM_{NOTi,t} + \varepsilon_{1,t}$

$SP_{i,t} = b_1 MQM_{i,t} + b_2 SP_{NOTi,t} + \varepsilon_{2,t}$

As an instrument for $SP_{i,t}$ (which can be either queue-jumping or mid-crossing), we use $SP_{NOTi,j}$, which is the daily average SP activity of other stocks listed on the same exchange, in the same market capitalization grouping (LARGE, MEDIUM, SMALL; excluding stock i). Similarly, as an instrument for $MQM_{i,t}$ we use $MQM_{NOTi,t}$, which is the average time-weighted bid depth (log of), quoted spread and relative spread, respectively, for other stocks listed on the same exchange, in the same market capitalization grouping (LARGE, MEDIUM, SMALL; excluding stock i). We estimate the simultaneous equation model by pooling observations across all stocks and days in the sample. To make the pooling meaningful, we de-mean all variables by deducting the stock-specific average and scale all variables by dividing by the stock-specific standard deviation to control for stock fixed effects. We report the estimated coefficients on top and p-values below. The symbols ***, ** and * indicate statistical signicance at the 0.1%, 1%, and 5% levels, respectively. Estimation is done with 2SLS with two-way clustered standard errors (i.e., stock and day).

	Panel A: Time-weighted depth						Panel B: Share volume					
	A.1: Queue-jumping			A.2: Mid-crossing			B.1: Queue-jumping			B.2: Mid-crossing		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large
a_1	0.342***	0.044	0.281*	0.202	-0.041	0.253	-0.294	-0.434	-0.216	-1.108*	-0.510	-2.583
	(0.000)	(0.802)	(0.022)	(0.376)	(0.889)	(0.439)	(-1.678)	(-1.559)	(-1.521)	(-1.972)	(-1.633)	(-0.641)
a_2	0.523***	0.371***	0.645***	0.602***	0.368***	0.719***	1.028***	1.029***	1.023***	1.231***	0.981***	1.887
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(9.603)	(7.522)	(11.148)	(6.132)	(8.021)	(1.249)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520
b_1	0.284**	0.058	0.251*	0.110*	-0.055	0.153	0.219***	0.222***	0.160***	0.239***	0.140*	0.323***
	(0.001)	(0.818)	(0.035)	(0.045)	(0.804)	(0.086)	(6.521)	(4.658)	(3.371)	(6.439)	(2.573)	(6.542)
b_2	0.421***	0.421***	0.548***	0.251***	0.276***	0.279***	0.490***	0.391***	0.623***	0.246***	0.344***	0.186
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(6.121)	(3.932)	(6.903)	(3.951)	(3.483)	(1.814)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520

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Table 32: **Queue-jumping and Mid-crossing: Quoted and Relative Spread**

This table reports the results from the analysis of the relationship between queue-jumping and mid-crossing activity and quoted spread (Panel A) and relative spread (Panel B)(both time-weighted). We measure queue-jumping activity as QJ, which is defined as 100 times daily queue-jumping dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). We measure mid-crossing activity as MID, which is defined as 100 times daily mid-crossing dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). Due to the potential simultaneity between quoted spread and relative spread, respectively, and queue-jumping and mid-crossing activity, we estimate the following two-equation simultaneous model for SP, which can be either QJ or MID, and and MQM, which can be either quoted spread and relative spread:

$MQM_{i,t} = a_1 QJ_{i,t} + a_2 MQM_{NOTi,t} + \varepsilon_{1,t}$

$SP_{i,t} = b_1 MQM_{i,t} + b_2 SP_{NOTi,t} + \varepsilon_{2,t}$

As an instrument for $SP_{i,t}$ (which can be either queue-jumping or mid-crossing), we use $SP_{NOTi,j}$, which is the daily average SP activity of other stocks listed on the same exchange, in the same market capitalization grouping (LARGE, MEDIUM, SMALL; excluding stock i). Similarly, as an instrument for $MQM_{i,t}$ we use $MQM_{NOTi,t}$, which is the average time-weighted bid depth (log of), quoted spread and relative spread, respectively, for other stocks listed on the same exchange, in the same market capitalization grouping (LARGE, MEDIUM, SMALL; excluding stock i). We estimate the simultaneous equation model by pooling observations across all stocks and days in the sample. To make the pooling meaningful, we de-mean all variables by deducting the stock-specific average and scale all variables by dividing by the stock-specific standard deviation to control for stock fixed effects. We report the estimated coefficients on top and p-values below. The symbols ***, ** and * indicate statistical signicance at the 0.1%, 1%, and 5% levels, respectively. Estimation is done with 2SLS with two-way clustered standard errors (i.e., stock and day).

	Panel A: Quoted spread						Panel B: Relative spread					
	A.1: Queue-jumping			A.2: Mid-crossing			B.1: Queue-jumping			B.2: Mid-crossing		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large
a_1	-0.312**	-0.426	-0.148	-0.436	-0.133	-0.462	-0.493**	-0.551	-0.288	-0.321	-0.076	-0.581
	(-2.601)	(-1.943)	(-1.372)	(-1.819)	(-0.768)	(-1.121)	(0.007)	(0.070)	(0.164)	(0.157)	(0.817)	(0.245)
a_2	0.683***	0.604***	0.732***	0.690***	0.682***	0.670***	0.631***	0.582***	0.684***	0.742***	0.719***	0.669***
	(8.407)	(6.378)	(8.671)	(11.321)	(9.029)	(5.348)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520
b_1	-0.187*	-0.213	-0.120	-0.160**	-0.0795	-0.197	-0.268***	-0.259*	-0.231*	-0.129**	-0.045	-0.223*
	(-2.522)	(-1.901)	(-1.534)	(-2.693)	(-1.058)	(-1.901)	(0.000)	(0.024)	(0.015)	(0.002)	(0.362)	(0.015)
b_2	0.448***	0.339***	0.647***	0.208**	0.304**	0.239	0.351***	0.282**	0.544***	0.221***	0.282***	0.203*
	(6.634)	(3.601)	(9.648)	(2.802)	(2.791)	(1.682)	(0.000)	(0.005)	(0.000)	(0.000)	(0.000)	(0.033)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520

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Table 33: **Queue-jumping and Mid-Crossing: Depth and Share Volume (Robustness)**
This table reports the results from the analysis of the relation between queue-jumping and mid-crossing activity and time-weighted bid depth (Panel A) and share volume (Panel B). We measure queue-jumping activity as QJ, which is defined as 100 times daily queue-jumping dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). We measure mid-crossing activity as MID, which is defined as 100 times daily mid-crossing dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). When analyzing the relation between QJ (or MID) and share volume, we use gross measure (i.e., not normalized to total consolidated volume). Due to the potential simultaneity between time-weighted bid depth (log of) and share volume (log of), respectively, and queue-jumping and mid-crossing activity, we estimate the following two-equation simultaneous model for SP, which can be either QJ or MID, and MQM, which can be either time-weighted bid depth or share volume We include as controls the return on SP500 and the VIX:

$$MQM_{i,t} = a_1 SP_{i,t} + a_2 MQM_{NOTi,t} + a_3 SP500_t + a_4 VIX_t + \varepsilon_{1,t}$$
$$SP_{i,t} = b_1 MQM_{i,t} + b_2 SP_{NOTi,t} + b_3 SP500_t + b_4 VIX_t + \varepsilon_{2,t}$$

	Panel A: Depth						Panel B: Share volume					
	A.1: Queue-jumping			A.2: Mid-crossing			B.1: Queue-jumping			B.2: Mid-crossing		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large
a_1	0.321***	0.055	0.252*	0.161	-0.046	0.163	-0.379	-0.491	-0.347	-1.167	-0.506	-5.510
	(0.000)	(0.738)	(0.032)	(0.494)	(0.872)	(0.644)	(-1.841)	(-1.112)	(-1.463)	(-1.723)	(-1.222)	(-0.392)
a_2	0.521***	0.358***	0.621***	0.594***	0.359***	0.691***	1.056***	1.036***	1.075***	1.238***	0.973***	2.913
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(11.349)	(6.021)	(9.091)	(5.988)	(8.269)	(0.558)
a_3	0.015	-0.017	0.035	0.030*	-0.016	0.044	0.0289	0.0381	0.0314	0.0277	0.0189	0.195
	(0.295)	(0.521)	(0.193)	(0.028)	(0.521)	(0.088)	(1.301)	(0.838)	(1.049)	(0.810)	(0.513)	(0.369)
a_4	0.000025	0.000090	-0.000042	-0.000094	0.000080	-0.00014	-9.294	1.765	-17.15	-10.11	3.175	-86.03
	(0.965)	(0.928)	(0.968)	(0.870)	(0.935)	(0.889)	(-0.734)	(0.072)	(-0.888)	(-0.551)	(0.133)	(-0.412)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520
b_1	0.261***	0.071	0.234*	0.096	-0.060	0.121	0.231***	0.218***	0.195***	0.236***	0.139**	0.330***
	(0.001)	(0.776)	(0.024)	(0.095)	(0.797)	(0.230)	(6.95)	(4.49)	(3.30)	(9.00)	(3.07)	(8.29)
b_2	0.408***	0.409***	0.541***	0.242***	0.283***	0.264***	0.451***	0.376***	0.540***	0.241***	0.344***	0.146
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(7.69)	(3.88)	(5.73)	(4.41)	(3.82)	(1.75)
b_3	0.026*	0.016	0.018	0.016	-0.0060	0.032	0.0280*	0.0273	0.0345	0.0104	0.00321	0.0278
	(0.045)	(0.505)	(0.499)	(0.270)	(0.793)	(0.249)	(2.08)	(1.16)	(1.65)	(0.70)	(0.11)	(1.32)
b_4	-0.00024	-0.00015	-0.00023	-0.000081	0.00010	-0.00020	-11.09	0.532	-19.37	-5.283	2.393	-12.15
	(0.628)	(0.885)	(0.812)	(0.886)	(0.914)	(0.810)	(-1.31)	(0.03)	(-1.38)	(-0.67)	(0.15)	(-0.97)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520

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Table 34: **Queue-jumping and Mid-Crossing: Quoted and Relative Spread (Robustness)**
This table reports the results from the analysis of the relationship between queue-jumping and mid-crossing activity and quoted spread (Panel A) and relative spread (Panel B)(both time-weighted). We measure queue-jumping activity as QJ, which is defined as 100 times daily queue-jumping dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). We measure mid-crossing activity as MID, which is defined as 100 times daily mid-crossing dollar volume on Alternative Display Facility (ADF) divided by daily consolidated dollar volume (volume computed during trading hours 9:30 AM - 4:00 PM ET). Due to the potential simultaneity between quoted spread and relative spread, respectively, and queue-jumping and mid-crossing activity, we estimate the following two-equation simultaneous model for SP, which can be either QJ or MID, and and MQM, which can be either quoted spread and relative spread. We include as controls the return on SP500 and the VIX:

$$MQM_{i,t} = a_1 QJ_{i,t} + a_2 MQM_{NOTi,t} + a_3 SP500_t + a_4 VIX_t + \varepsilon_{1,t}$$
$$SP_{i,t} = b_1 MQM_{i,t} + b_2 SP_{NOTi,t} + b_3 SP500_t + b_4 VIX_t + \varepsilon_{2,t}$$

	Panel A: Quoted spread						Panel B: Relative spread					
	A.1: Queue-jumping			A.2: Mid-crossing			B.1: Queue-jumping			B.2: Mid-crossing		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large	Full sample	Small	Large
a_1	-0.329*	-0.547*	-0.135	-0.450	-0.223	-0.442	-0.461**	-0.602	-0.271*	-0.303	-0.132	-0.538
	(-2.301)	(-2.012)	(-0.861)	(-1.601)	(-0.739)	(-0.948)	(0.002)	(0.090)	(0.046)	(0.103)	(0.685)	(0.199)
a_2	0.641***	0.463***	0.709***	0.639***	0.576***	0.652***	0.611***	0.500***	0.669***	0.714***	0.661***	0.659***
	(12.344)	(4.501)	(8.029)	(10.472)	(6.322)	(5.773)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
a_3	-0.048**	-0.102**	-0.036	-0.055**	-0.085**	-0.031	-0.028	-0.068*	-0.017	-0.039***	-0.057*	-0.015
	(-2.612)	(-2.861)	(-1.443)	(-3.067)	(-2.666)	(-1.021)	(0.057)	(0.012)	(0.608)	(0.000)	(0.020)	(0.624)
a_4	-17.685	-30.339	-9.413	-8.718	-11.666	-9.595	0.00014	0.00027	0.00017	0.00023	0.00027	0.00020
	(-1.448)	(-1.459)	(-0.488)	(-0.810)	(-0.594)	(-0.501)	(0.781)	(0.774)	(0.846)	(0.636)	(0.758)	(0.841)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520
b_1	-0.187**	-0.319*	-0.0924	-0.171***	-0.129	-0.174*	-0.262***	-0.322**	-0.214*	-0.121**	-0.067	-0.201*
	(-2.991)	(-2.102)	(-0.811)	(-3.504)	(-1.189)	(-1.968)	(0.000)	(0.008)	(0.011)	(0.003)	(0.380)	(0.010)
b_2	0.403***	0.284**	0.583***	0.201***	0.292**	0.211*	0.348***	0.259*	0.528***	0.219***	0.268***	0.194
	(6.988)	(2.758)	(7.351)	(3.501)	(3.262)	(2.278)	(0.000)	(0.013)	(0.000)	(0.000)	(0.000)	(0.057)
b_3	-0.000973	-0.0573	0.0221	-0.0113	-0.0282	0.0182	0.0086	-0.035	0.026	0.0040	-0.016	0.027
	(-0.049)	(-1.428)	(0.779)	(-0.678)	(-0.809)	(0.722)	(0.525)	(0.230)	(0.291)	(0.789)	(0.583)	(0.212)
b_4	-27.22**	-28.25	-27.73	-10.539	-0.796	-16.412	-0.000084	0.000084	-0.00013	0.0000055	0.00015	-0.000072
	(-2.941)	(-1.582)	(-1.843)	(-1.302)	(-0.062)	(-1.131)	(0.868)	(0.930)	(0.883)	(0.992)	(0.875)	(0.933)
Observations	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520	7,560	2,520	2,520