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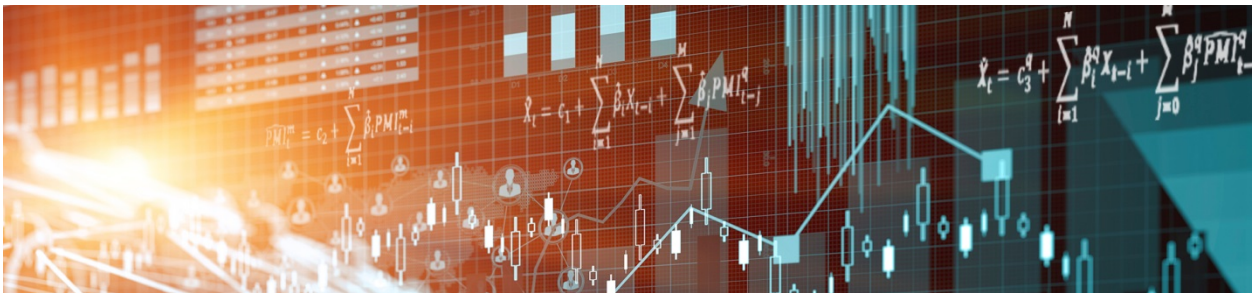

by Faith Chin and Corey Garriott

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Options Decimalization

by

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Abstract

We document the outcome of an options decimalization pilot on Canada's derivatives exchange. Decimalization improves measures of liquidity and price efficiency. The impact differs by the moneyness of an option and is greatest for out-of-the-money options. In contrast with equity studies, decimalization improved depth near the best prices and improved liquidity for larger trades. We conclude with advice on decimalizing options: options that benefit most have underlying volatility less than 40, underlying equity bid-ask spread less than 50 basis points, at least one trade a day, and a distribution of depth skewed toward marketable prices.

Bank topics: Financial markets; Market structure and pricing; Financial system regulation and policies
JEL codes: G20; G14; L10

Résumé

Dans la présente étude, nous analysons les résultats des projets pilotes de décimalisation du prix des options qui ont été menés par la bourse canadienne des produits dérivés. La décimalisation améliore les mesures de la liquidité et de l'efficience des prix. Les effets de cette opération varient selon le degré de parité d'une option et sont plus marqués pour les options hors du cours. À la différence des études relatives à la décimalisation sur les marchés des actions, la présente étude révèle que la décimalisation accroît la profondeur du marché des options dans le haut de la fourchette des cours et améliore la liquidité pour les transactions de grande ampleur. Nous concluons en donnant quelques conseils sur la décimalisation des options : cette opération est plus avantageuse pour les options qui ont une volatilité sous-jacente inférieure à 40, qui affichent un écart acheteur-vendeur sous-jacent du cours des actions de moins de 50 points de base, qui font l'objet d'au moins une transaction par jour, ou qui présentent une distribution de la profondeur du marché asymétrique en faveur des meilleurs cours.

Sujets : Marchés financiers; Structure de marché et fixation des prix; Réglementation et politiques relatives au système financier
Codes JEL : G20; G14; L10

Non-Technical Summary

Operators of stock exchanges, derivatives exchanges, and other venues for securities trade must choose an operational parameter called "tick size." It is the minimum unit of variation of a security's price. For example, a security with a tick size of five cents may trade for the prices of $10.35, $10.40 or $10.45, but such a security may not trade for the price of $10.37. The tick size is a determinant of the profits earned by market makers, who provide the service of acting as counterparties on demand for a trading venue's customers. Market makers are in a high-volume, low-margin business. For market makers the tick size equals the minimum difference between a buying price and selling price; it is the minimum revenue they can make. A reduction in tick size reduces the floor on a market maker's margin, which, multiplied by high volume, may result in big changes in profits.

We know trading-venue operators seek a small tick size because it redistributes rents from market makers to the trading venue's end users. A small tick size attracts more end users and hence is good for a trading venue's business. However, we also know there is a minimum tick size that market makers can bear, which is determined by the competitiveness of market making and the volume of trading. If the tick size is too small it drives away market-making interest, not only by reducing margins but also by enabling gaming strategies that rely on small price increments.

Event studies on historical tick size changes, often called "decimalizations," show that if trading venues choose the right securities for tick size changes, it can benefit markets overall. So far, almost all the studies look at decimalization on stock markets. We contribute to this literature by instead studying decimalization in an options market, the

Montréal Exchange. There are enough differences between an options market and a stock market that results could be different for options. Options are derivatives and could be poor candidates for a smaller tick size because they are much less frequently traded compared with stocks and have smaller trading communities, including fewer market makers.

We find instead that options tolerate a lower tick size well. Metrics of liquidity and price efficiency improve for almost all the options that were decimalized. Some of the results imply that options benefit more than stocks. For example, market depth—a measure of the number of contracts available for trading—is supposed to decline at the most competitive prices, but for options we find it increases. We study how the impact of decimalization varies by the characteristics of the option, and we provide some advice for exchanges about which options to decimalize. The usual rule of "decimalize the liquid securities" applies. Last, we have results of interest to specialists. The impact of decimalization is stronger for out-of-the-money options, meaning options that, if exercised, would have negative value. This is of interest to the growing literature on options liquidity, as it confirms intuitions that options differ substantially by moneyness.

1. Introduction

Decimalization decreases the tick size, which is the minimum numerical increment by which a security's price may differ. On equity markets, decimalization has been shown to tighten quoted spreads and has ambiguous effects on quoted depth (Bessembinder 2003; Goldstein and Kavajecz 2000; Griffiths et al. 1998). Although the academic literature has covered equity decimalization well, there is little written on decimalization in options.[1] It is important to understand decimalization in the context of options because it can alter costs and behaviours in a market that enables large-scale transfer of risk. Interest in tick sizes is resurfacing due to the 2012 JOBS Act, which gave the US Securities and Exchange Commission new authorization to increase tick sizes. This paper fills the gap in the evidence on options by documenting the impact of an options decimalization program implemented on the Montréal Exchange in 2008 and 2010.

We find that decimalization improves options liquidity and price efficiency. In contrast with equity studies, decimalization improves measures of depth near the best bid and ask and improves liquidity for large trades. The outcome varies by moneyness—out-of-the-money options benefit the most, while in-the-money options benefit the least. We use the cross-section of the results to generate advice for options exchanges. The best candidate options are those with good liquidity conditions—low volatility in the underlying, tight bid-ask spreads, and at least one trade per day. In addition, candidate options do better if most of their depth is located near the best bid and ask prices.

[1] The equity literature has explored the impact of decimalization in the cross-sections of stock, trader type and trade size. While trading costs for small trades improve, evidence for large trades is mixed (Bollen and Busse 2006; Chakravarty, Panchapagesan and Wood 2005; Jones and Lipson 2001). Decimalization in stock markets changes trader behaviour by increasing price revisions (Chung and Chuwonganant 2002), by moving trading activity to the downstairs market (Griffiths et al. 1998), and by increasing behaviour consistent with quote matching (Edwards and Harris 2001; Bacidore, Battalio and Jennings 2003).

Theory on tick size predicts that decimalization should trade off greater competition on price with weaker incentive to show depth (Werner et al. 2015; Foucault, Kadan and Kandel 2005; Goettler, Parlour and Rajan 2005; Harris 1997). Decimalization intensifies price competition because a smaller tick makes it cheaper to underbid the current best price, so there should be more underbidding. On the other hand, a smaller tick decreases the reward for quoting large limit orders. On a limit-order book, the reward for quoting limit orders is higher precedence in the trading queue (typically determined by price-time priority). If the tick size is too small, any trader may jump ahead in the queue for a trivial concession in price, in which case precedence is not a particularly valuable reward (Cordella and Fouault 1999). Since there are countervailing forces, trading venues have a business need to set the tick size just right.

Our results speak to this trade-off and in particular to its characterization in Werner et al. (2015), which predicts that the trade-off is positive for securities that are more liquid and negative for securities that are less liquid. In our results, the more liquid out-of-the-money options do best, and options with good liquidity conditions such as liquid and stable underlying also do well. Using Werner et al. (2015), we produce a test for decimalization drawing from its notion of a "liquid book." If the shape of the order book is skewed toward the best bid and ask prices, we predict a positive effect on liquidity *ceteris paribus*. Last, we confirm the model's prediction that decimalization might decrease liquidity exactly at the bid-ask spread but increase depth near the bid-ask spread. We use the results to give criteria for which options to decimalize.

It is necessary to test decimalization theory specifically for options because it is not straightforward to apply to options the results from the equity literature. While tick size

changes in equity markets have been successful with investors (Christie and Schultz 1994), in other markets, the decimalization has diminished a market's appeal to participants, as with the FX platform EBS (Gencay and Mahmoodzadeh 2015). Options might be different from stocks because options are less liquid and hence poorer candidates for decimalization. Another reason to test decimalization for options is that arguably, decimalization could have negligible effects. Options liquidity is substantially dependent on underlying market liquidity (Goyenko, Ornthanalai and Tang 2015), and in theory, it can be well described as simply an expression of hedging and inventory costs (Garleanu, Pedersen and Poteshman 2009). Our paper finds that decimalization does change options liquidity, which shows that microstructure effects such as tick size do play a role in options markets.

Our major findings are as follows. First, decimalization improves measures of liquidity, including depth measures and volume-weighted spread measures. The positive effect on depth and volume-weighted spreads contrasts with results from equity, in which these measures typically suffer. Specifically, we find depth near the top of the book improves by 5.1 to 12.2 contracts (depending on option moneyness), even as depth overall falls by 2.6 to 11.5 contracts. Market makers do not universally decrease limit-order sizes, as found by Goldstein and Kavajecz (2000). Instead, market makers act as described in Werner et al. (2015) to increase depth in certain segments of the book and decrease it elsewhere. In addition, we find volume-weighted measures of transaction costs improve. Volume-weighted liquidity metrics put more weight on the liquidity experienced by large trades. The result is interesting because, again, it contrasts with equity studies in which large or institutional trades perform worse (Bollen and Busse 2006; Chakravarty,

Panchapagesan and Wood 2005; Jones and Lipson 2001). In general, the results suggest options markets are sufficiently competitive that nickel tick sizes are too large.

Second, we find there is a moneyness structure to the impact of options decimalization. Sorts of the impact by price and by moneyness show that decimalization particularly improves low-priced options and out-of-the-money options, which are similar classes. To disentangle the effect, we generate a dataset of the treatment effects and explain them using price and moneyness. The effects (which already have price and moneyness controls) are regressed again on price and moneyness. For the relative bid-ask spread, there remains a moneyness structure to decimalization even after controlling for price. The result confirms the literature on options liquidity that distinguishes the out-of-the-money market in terms of investor composition (Christoffersen et al 2015; Bollen and Whaley 2004). The outcome of decimalization suggests that relatively out-of-the-money options are also distinguished by a potential for price competition.

Last, we use the results to produce some advice to trading venues about which options to decimalize. Empirical guidance is useful to exchanges, which have a business need to set the right tick size. We generate the advice by studying the effect of decimalization sorting by options-specific liquidity determinants: the underlying volatility, number of trades, and the underlying relative bid-ask spread. Based on the results, we advise trading venues to decimalize options classes with underlying volatility of less than 40, with equity bid-ask spreads less than 50 basis points, and with trades at least once a day. Moreover, the order book can be used to test whether to decimalize. We advise that depth improves for options order books in which two-thirds of depth is located within the first five cents inside the book.

2. Data

The data in this study are from the Montréal Exchange (MX). The MX was founded 1874 as the Montréal Stock Exchange and today operates as Canada's derivatives exchange. It is an electronic exchange that lists futures and options on underlying equity, bond and money-market instruments. The MX provided data from January 2008 to December 2010 on all listed equity options, which are American. The data contain reports on all order insert, cancel, update and fill actions, as well as both sides of all trades. Orders and trades have fields for price, quantity, side, initiation, and millisecond timestamp. In addition, certain limit orders are marked as "bulk quote" orders. Bulk quotes are limit orders that can be placed only by MX market-maker accounts, and we use them to study market-maker liquidity.

In 2008 and 2010, the MX ran five decimalization pilots named "Penny Pilots" after a similar program in the United States. The MX pilot dates did not coincide with those in the United States. The MX had decimalized the Canadian stocks first in all but two cases (Goldcorp Inc. and Yamana Gold Inc.) in which the United States venue decimalized a Canadian cross-listed stock. Each MX decimalization event changed options for roughly 10 stocks at a time. Table 1 shows a list of the stocks and decimalization dates.

TABLE 1 ABOUT HERE

The pilots provide useful statistical instruments for two reasons. First, the events are staggered over five dates. The staggering provides a natural time-series control that limits the exposure of the study to confounding trends present during one particular

window of time.[2] Second, the MX decimalized options only partially, opening penny price points for options prices below $3.00, but not for those above $3.00, which retained a nickel price grid. The partiality of the treatment provides a set of natural control observations for each treatment observation. The control observations in this study are options with treated underlying but with prices above $3.00. Since these options are for the same underlying stock as the treatment options, they share risk determinants and liquidity determinants with the treatment options. The similarity of the controls to treatments stands in contrast to equity-market liquidity studies, which typically draw control observations from securities issued by different companies.

To form a dataset, we extract a suite of liquidity and price-efficiency metrics common in microstructure analysis. We choose a set of liquidity metrics that capture several dimensions of transaction cost: small trades vs. large trades, relative changes vs. absolute changes, and the cost now vs. the cost 30 seconds later. First, we compute the daily *bid-ask spread*, the average time-weighted difference between the bid and ask prices; and the daily *market-maker depth*, the cumulation of market-maker limit-order sizes in a price interval some distance in cents from the inside quote. Depth is expressed in lots, and one lot is for 100 options. We focus on market-maker orders since their liquidity supply is the most likely to be affected by competition. Next, we compute the daily *effective spread*, the average difference between a trade price and the contemporaneous midquote signed by initiation of trade (positive quantity for buy-initiation, negative for sell); the daily *price impact*, the difference between the midquote at trade time and the midquote 30 seconds

[2] None of the events take place between September 2008 and 2009, the dates from the fall of Lehman Brothers to the implementation of US financial stabilization measures.

later signed by initiator of trade; and a daily *Kyle's lambda*, the regression coefficient of the log 30-second return after a trade on the dollar value of the trade signed by the initiator of the trade. To distinguish absolute changes from relative changes, we compute the bid-ask spread, effective spread and price impact statistics both in dollar units and in relative percentages from the midquote (basis points or bps). In addition, to distinguish changes for smaller trades from those for larger trades, effective spreads and price impacts are averaged using both trade weighting and volume weighting. Volume weighting better represents realized liquidity for larger trades.

For price-efficiency metrics, we collect a series of observations of the 15-second *midquote*, the midpoint price between bid and ask observed every 15 seconds. Using the 15-second midquote, we compute three metrics of price predictability: The daily *midquote return volatility*, the standard deviation of first differences of the midquote, and the daily *midquote autocorrelation*, which is the correlation between midquote first differences and lagged first differences. We compute the volatility and autocorrelation at both a 15-second frequency and a one-minute frequency. Using that, we compute the daily midquote *variance ratio*, which is the absolute value of the ratio of the one-minute return volatility with four times the 15-second volatility minus one.

FIGURE 1 ABOUT HERE

Figure 2 shows the daily averages of selected volume and liquidity metrics through the sample period and for options for stocks in the Standard & Poor's (S&P) Toronto Stock Exchange (TSX) 60 index. Liquidity and volume on MX improve between 2008 and 2010.

The 2008 global financial crisis is visible. Summary averages for options for stocks in the S&P TSX 60 index are shown in Table 2.

Second, we draw from Bloomberg the daily equity close price, daily equity closing bid-ask spread, and the daily equity 30-day rolling close price volatility (realized volatility). From the Bank of Canada website, we draw the daily Bankers' Acceptance rates, a proxy for the "risk-free" rate for Canada. We use these statistics in the binomial American Black-Scholes options pricing model to compute the daily option delta.[3]

Finally, we clean the data. We drop options observations in which the time to expiry was greater than 365 days or less than one week, and in which the midquote was greater than $10 or less than $0.10. Last, we collect an event-study subsample from the data. The subsample consists of daily observations of the above statistics during a two-month calendar period around each decimalization treatment date.

3. Research design

The methodology in this paper is the differences-in-differences (DiD) event study. To produce a regression dataset to use in DiD, we aggregate the data two ways. First, for each of the metrics and for each option underlying stock, we average the metric for options with prices above $3.00. This is called the control index. We will subtract from each metric its control index to perform the first difference of the DiD.

Second, for options with prices below $3.00, we average the liquidity and price efficiency metrics in six bins. The bins are by type (put or call) and moneyness (in-, at- or out-of-the-money). Moneyness is measured by the Black-Scholes delta, with an absolute

[3] We are grateful to Github for the free Python implementation of the Black- Scholes binomial model in pyfin.py.

value of delta one-eighth to three-eighths being out-of-the-money, three-eighths to five-eighths at-the-money, and five-eighths to seven-eighths in-the-money. Treatment observations that have absolute delta above seven-eighths or below one-eighth are dropped. The averaging reduces redundancy in options data, as participants are roughly indifferent between options with the same type and nearly the same strike.

To verify that the treatment and control observations have parallel trends, we graph the bid-ask spread, relative effective spread, and inside depth to 5 cents, and a one-minute return autocorrelation averaged for the treatment options and control indices in the panels of Figure 2.

FIGURE 2 ABOUT HERE

In the panels, the impact of decimalization is clearest in Panel A (bid-ask spread) and Panel B (relative effective spread). The treatment effect is visible in Panel C (depth) as an increase in the distance between the treated and control options, though the depth metric is clearly more volatile. The treatment effect is visible in Panel D (autocorrelation) since the treatment autocorrelations are all greater than the controls before decimalization and less than the controls after decimalization.

Figure 2 shows that the treatment and control series have different levels in certain metrics. There is a level difference because the control options were selected by criteria that ensure that they have higher prices and hence greater moneyness (more in-the-money). Table 2 shows that relatively in-the-money options have somewhat different trading and liquidity characteristics. The different moneyness of the controls could be a

problem if there are trends associated with moneyness that are coincident to the date of the decimalization treatments. It is not a problem in this study because (in unreported results) we verify that the control series do not exhibit a statistically significant trend for the spreads, depths and price impacts in all six options type-moneyness categories. For robustness, we include in our regression model controls for moneyness and price anyway.

To identify the treatment effect, we fit an event-study regression on the difference of the metric, with its control index on a post-period dummy and two control variates:

$$\Delta metric_{i,t} = c_i + \beta_i \, post_{i,t} + \delta_i X_{i,t} + \varepsilon_{i,t},$$

where subscript *i* indexes the treatment option type-moneyness bin and subscript *t* indexes the date of observation in event time (negative numbers for trading days before the decimalization event, positive for after). *Δmetric* is the difference between the metric for the treatment option bin and the control index. Coefficient β is thus the differenced difference or the treatment effect, the parameter of interest in our analysis. The fit coefficients *c*, β and δ are subscripted by *i* because we fit the model once per option type-moneyness bin. *Post* is a dummy equalling 1 after the treatment date for the option underlying. There are no option-underlying fixed effects because the independent variable is the first difference, so the effects are already differenced out. There are no type-moneyness fixed effects because the model is fit once per type-moneyness. Standard errors are clustered by underlying stock.

The variables in *X* are the controls for the option moneyness and price. The moneyness control is the log moneyness (measured by the absolute Black-Scholes delta)

averaged for the options in a bin. The price control in most specifications is the average midquote price. However, relative spread metrics (relative bid-ask spread, relative effective spread and relative price impact) do not scale in the price but in the inverse price because these metrics have price in the denominator. It is best to use explanatory variables that vary linearly in the price or else there can be model misspecification—the treatment effect may be over- or under-attributed due to curvature in the explanatory variables. Therefore, for relative-spread metrics, we use the inverse price as the price control. Last, depth metrics do not scale linearly in the price, either. For these metrics, we use the log price as the price control. To illustrate, Figure 3 plots the sample average dollar-value bid-ask spread, relative bid-ask spread, and depth against the transforms of the price. The graphs show a near-linear relationship as measured by linear correlation.

FIGURE 3 ABOUT HERE

For the last regression in this paper, we generate a new dataset. We run the event-study regression once per underlying stock, option type and option moneyness. We collect the stock-type-moneyness effects as $\beta_{s,i}$, where subscript *s* indexes the stock. The collected effects constitute a new independent variable for the last regression in the paper. The last regression explains the treatment effects by regressing them on characteristics of the option. We explain the treatment effects by regressing them on the pre-period metric, option price, option delta and option stock underlying fixed effects.

4. Results

To economize on space, in Tables 3–5 we omit coefficient estimates for the control variates, as it is well-known that options-liquidity metrics scale in moneyness and price. We also omit standard errors and simply report significance stars at 1 per cent, 5 per cent and 10 per cent levels. These economies enable us to report all cross-sections of treatment effects on three pages.

4.1 Differences-in-differences

Table 3 gives the DiD impact on metrics of bid-ask spread, effective spread, and price impact for six bins of options by type and moneyness.

TABLE 3 ABOUT HERE

Overall, options decimalization improves the bid-ask spread, effective spread and price impact. Depending on moneyness, the bid-ask spread decreased by 1.6 cents to 1.9 cents, and the effective spread decreased by 1.9 cents to 3.7 cents. The price impact expressed in cents did not change with statistical significance, suggesting that decimalization interacts weakly with informational frictions and even more with market power. The impact of decimalization on metrics expressed in relative units (bps) is more wide ranging. Depending on moneyness, the relative bid-ask spread decreased by 98 to 468 bps, the relative effective spread by 122 to 389 bps, and the relative price impact from 27 to 104 bps now with statistical significance. The results for the volume-weighted and relative volume-weighted metrics are not substantially different from those for the trade-

weighted versions, meaning that the impact of decimalization for larger trades is not different from that for smaller trades. One exception to the general trend of improvement is Kyle's lambda. This metric deteriorates for calls, though the deterioration is without statistical significance.

There is a moneyness structure to the impacts on the relative metrics. For example, the impact on the relative bid-ask spread is greater for out-of-the-money options, with an impact on the order of 400 bps. The same number is only around 100 bps for in-the-money options. One hypothesis that can explain the moneyness structure is that options markets differ substantially by moneyness in terms of investor composition. However, the structure might also derive from a simple price effect: in-the-money options are more expensive, so the same absolute impact has a smaller relative impact. We explore the possibility that the impact of decimalization does not vary due to option type-moneyness but simply due to price in section 4.3.

Table 4 reports the impacts on depth, volatility and price-efficiency metrics.

TABLE 4 ABOUT HERE

Decimalization improves depth where it is most valuable to traders. Inside depth, at available prices within 5 cents of the best bid and ask, increases by 5.1 to 12.2 contracts. Inside depth at prices within 20 cents increases by 0.7 to 7.6 contracts, though without much statistical significance. In contrast, depth decreases for prices located further from the best bid and ask. Depth for the price interval 5 to 20 cents within the best bid and ask decreases by 2.9 to 7.0 contracts. Depth overall (measured as depth 50 cents from the

midquote) decreases by 2.6 to 11.5 contracts. Together, the results mean market makers are redistributing depth from locations far from the best prices to locations nearer the best prices. This result is corroborated by the improvements in the relative price-impact metric, as price impact is partially an expression of latent depth.

We confirm the result from equity markets that limit-order size at exactly the best bid and offer decreases. Inside depth at the best quotes decreases 5.5 to 9.5 contracts. In addition, we have already confirmed overall depth decreases. While these measures of depth decrease, they are not the most relevant measures of depth in this context. Depth only at the best bid and ask is misleading because decimalization opens new price points between the new, tighter bid-ask spread and the old, wider spread. A comparison of depth before and after decimalization should include the price points that did not previously exist, which are provided by the metric of the inside depth to five cents. Depth "overall" is similarly a misleading measure because limit orders sufficiently far from the best quotes are never accessed.

Decimalization decreases volatility. Its effect on 15-second return volatility for all types and moneyness is a decrease of around 0.2. Its effect on one-minute return volatility is a decrease of around 0.3. This effect is largely mechanical because standard deviation increases in the square of the price change. Decimalization allows a price to drift on a more granular set of values, which means price changes tend to be smaller.

Last, decimalization improves metrics of price efficiency. Studies on decimalization do not often test price efficiency because changes in price competition are not generally expected to affect the predictability of prices. There is still potential for an effect because the midquote of a nickel spread can be a poor representation of the true price compared

with the midquote in a more granular price grid. Decimalization decreases return autocorrelation at 15 seconds with limited statistical significance, and decreases return autocorrelation at one minute with statistical significance in every option category. It also decreases the variance ratio with statistical significance.

4.2 Sorting the DiD by price, underlying volatility, trades and underlying liquidity

Table 5 reports the results of the DiD event study conducted on terciles of the sample sorted by price, equity volatility, trades and equity liquidity.

TABLE 5 ABOUT HERE

Panel A shows the treatment effect sorted by price terciles of \$0–1, \$1–2 and \$2–3. The results provide evidence for a price effect changing the impact of decimalization. Specifically, for options prices \$0–1, the impact on the relative spread is greater than 400 bps. For prices between \$1–2, the impact is smaller, around 150 bps. For prices greater than \$2, the impact is in the order of 100 bps. The same measure expressed in cents does not increase or decrease in the options price. Specifically, for options with prices below \$1, the impact is 1.7 cents, yet for options prices above \$2, the impact is still 1.6 cents to 1.9 cents. A natural explanation is that it is a price effect, as the relative bid-ask spread is the bid-ask spread divided by the price. In section 4.3, we attempt to explain the treatment effect using both price and moneyness to see whether both are good explainers of the treatment effect.

Panels B to D show the treatment effect sorted by terciles of underlying volatility, number of trades and underlying liquidity. The panels show that the middle-liquid options see the largest improvements to the bid-ask spread and depth. For volatility, the largest impact on the bid-ask spread is for the middle tercile: 2.1 cents. For the number of trades, the largest impact on the bid-ask spread is for the middle tercile: 2.6 cents. For the underlying stock liquidity, the largest impact on the bid-ask spread is for the middle tercile: 2.6 cents. For inside depth to 5 cents, the same is true after eliminating statistically insignificant coefficients. The result that the middle terciles do best is somewhat in contrast to theory, which predicts that liquid securities benefit most. One explanation is that most liquid options are already so liquid that they have less to gain.

4.3 Explaining treatment effects on depth using pre-treatment depth

Continuing the analysis in section 4.2, we ask whether the treatment effect also varies in the shape of the order book, as predicted in Werner et al. (2015). We search for a shape effect by explaining the treatment effect using two depth variables for different segments of the book. Since there are two variables, we use multivariable regression and not just sorts. Table 6 shows the results of a regression in which we explain the treatment effects on bid-ask spread and depth using pre-decimalization liquidity, option price, option delta and fixed effects for underlying stock.

TABLE 6 ABOUT HERE

Before studying depth, we use the model setup to confirm a previous result. Column 1 shows that the effect of decimalization varies by moneyness even after controlling for price. This confirms the result of the sort by moneyness in section 4.2. Column 1 is a regression on the relative bid-ask spread. It shows that an option with a relative spread wider by 100 bps benefits by 8 bps more. As shown before, for wider spreads there is more room for improvement. The model has significance for both the price and delta coefficients, which means the treatment effect varies by moneyness even after controlling for price. This finding confirms recent work showing that out-of-the-money markets are different. We add that one way they differ is that they are more competitive.

Columns 2 and 3 give evidence for an order-book test to determine which options to decimalize. The test measures whether most depth is located near the best bid and ask. Column 2 shows that depth to 5 cents improves by a quarter-contract for every existing unit of depth to 5 cents. Column 3 shows that depth to 20 cents also improves in existing depth to 5 cents, this time by about three-quarters of a contract. However, depth to 20 cents deteriorates in existing depth to 20 cents, which means that depth in different parts of the book carry opposite predictions for the treatment effect. If enough depth is located within 5 cents compared with outside 5 cents, the regression predicts depth to 20 cents will improve. Quantitatively, the coefficients of 0.77 and -0.58 imply that at least two-thirds of the depth within 20 cents of the spread should be distributed at or adjacent to the best bid and ask for a successful decimalization.

5. Conclusions

We find that decimalization can improve options market quality as measured by a suite of liquidity and price-efficiency metrics. The liquidity metrics capture several dimensions of transaction cost: small trades vs. large trades, relative changes vs. absolute changes, and the cost now vs. the cost 30 seconds later. Not surprisingly, we find decimalization can tighten spread measures. What is more novel in light of theory and results from equity markets is that decimalization can improve option depth near the best bid and ask prices (and measures related to latent depth such as price impact). That depth near best prices would improve suggests that nickel spreads for many options may be too large.

We find there is a moneyness structure to the impact of options decimalization. Sorts of the impact by price and by moneyness show that decimalization has a greater impact on low-priced options and out-of-the-money options, which are similar classes of options. To disentangle the effect, we generate a dataset of the treatment effects and explain them using price and moneyness. The effects (which already have price and moneyness controls) are regressed again on price and moneyness. For the relative bid-ask spread, there remains a moneyness structure to decimalization even after controlling for price. This confirms findings that options markets differ substantially by moneyness in terms of investor composition, and we can add that they also differ by price competition.

Last, we conclude with limited advice to trading venues. Assuming the results in this study are representative, options that do best after decimalization are those with good liquidity determinants: underlying volatility of less than 40, an equity underlying bid-ask spread of less than 50 bps, and a number of trades of at least one a day. These criteria could be used to create a candidate set of options for decimalization. Moreover, we offer a test for

decimalization based on the distribution of depth on the order book. The coefficients on pre-period depth in Table 6 imply that successful options had at least two-thirds of depth in the first 5 cents of a price interval from the best bid and ask to 20 cents within the best bid and ask. In other words, options that are good candidates for decimalization have a depth profile skewed toward the best quotes.

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Figure 1: Liquidity history of the data sample. This figure plots four daily options liquidity variables for MX options with TSX S&P 60 underlying from 2008 to 2012. Measures of quantities use the left-hand axis, and measures of basis points use the right-hand axis. *Total depth* is the cumulation of the quantity of all limit orders at distances 10 cents from the midquote. *Total traded volume* is the sum total of trading quantity. *Relative bid-ask spread* is the average difference between ask and bid divided by the midquote, expressed in basis points. *Relative effective spread* is the average of the sign of trade times the difference between the trade price and the midquote divided by the midquote, expressed in basis points.

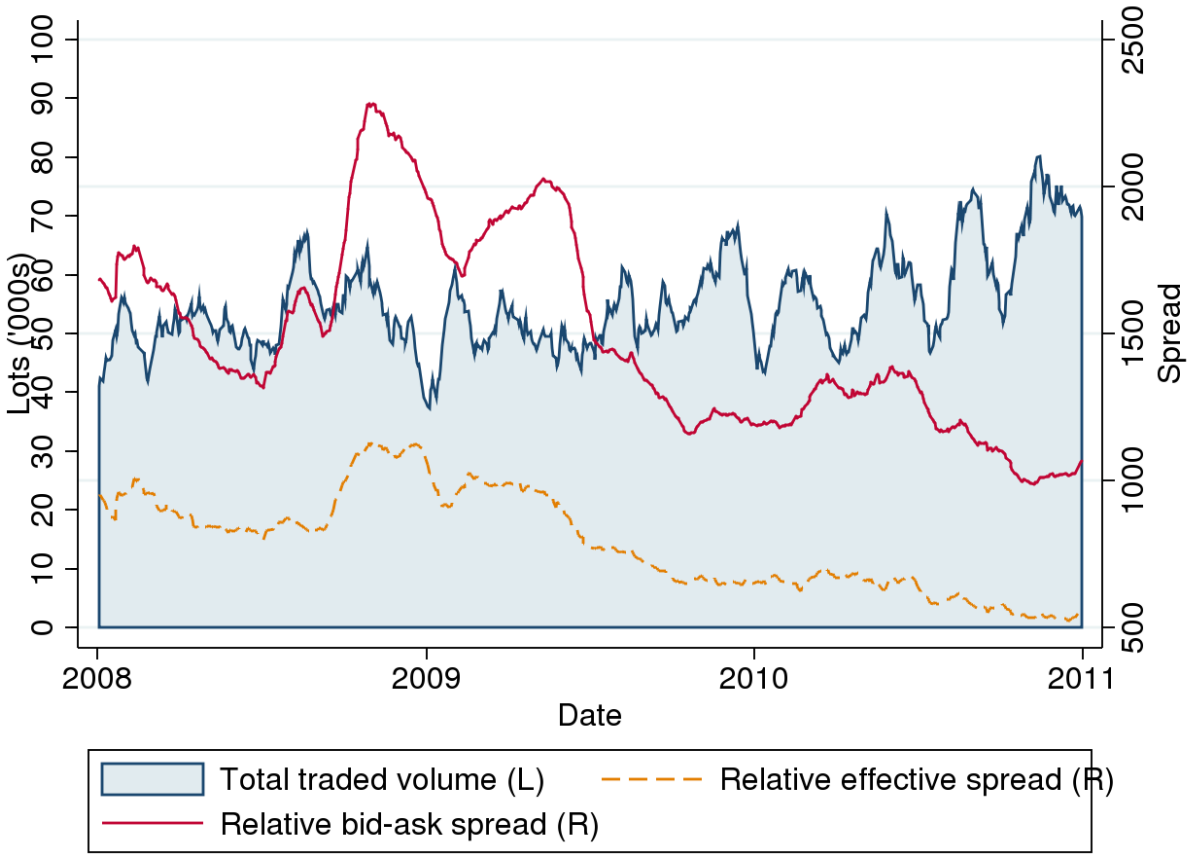


Figure 2: Parallel trends. These figures depict the average daily liquidity metrics for treatment options and the liquidity index for control options averaged during the event periods of one month before and after decimalization. The graphs are presented in event time, so positive date indices represent days after decimalization. Solid blue dots represent a metric for treatment stocks; hollow red dots represent a metric for treatment stocks. *Bid-ask spread* is the average difference between ask and bid. *Relative effective spread* is the average of the sign of trade multiplied by the difference between the trade price and the midquote divided by the midquote, expressed in basis points. *Inside depth to 5 cents* is the cumulation of limit-order size in a price window five cents within the prevailing bid and best offer. *One-minute return autocorrelation* is the correlation of the log return and lagged log return at one-minute frequency.

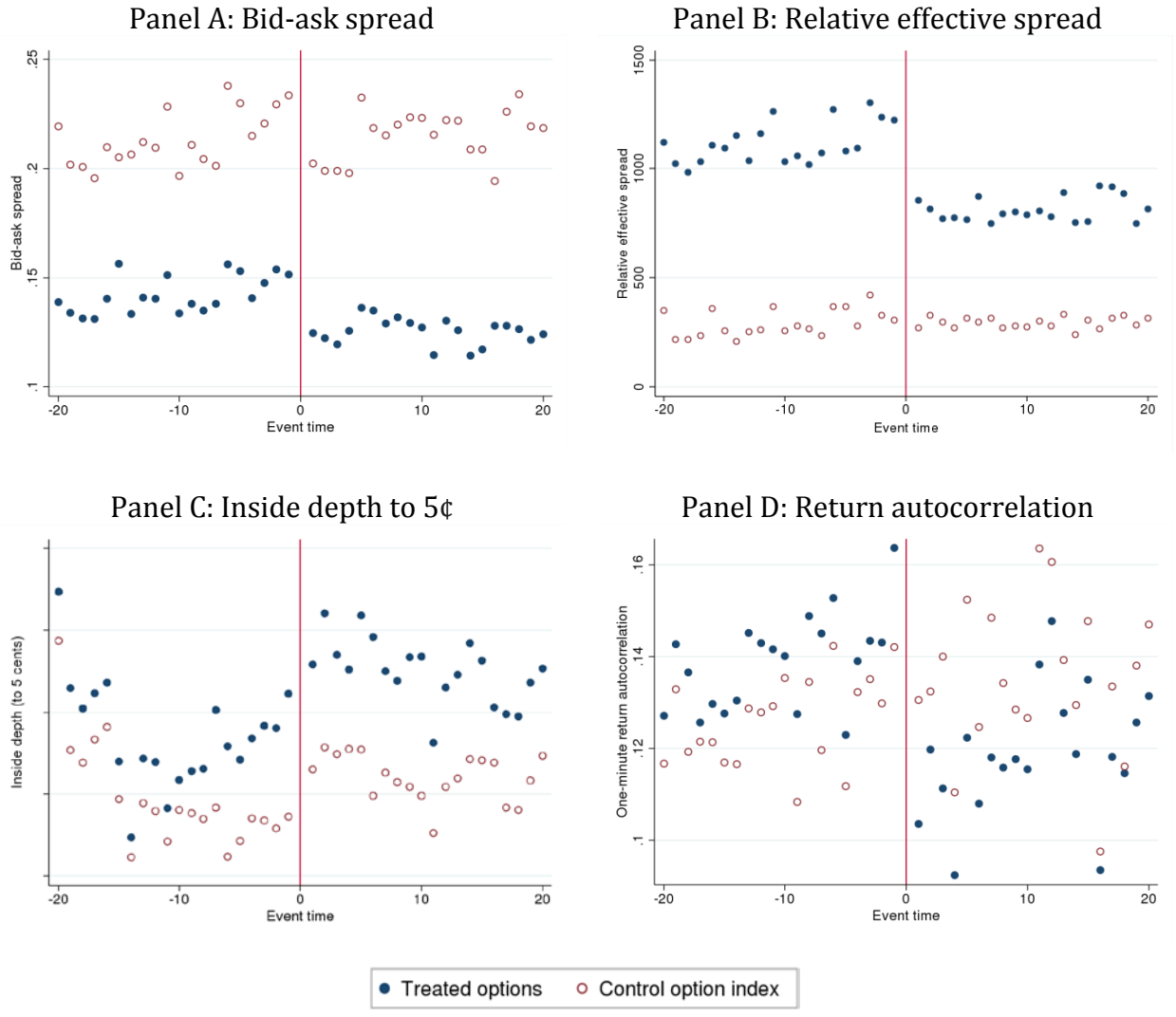
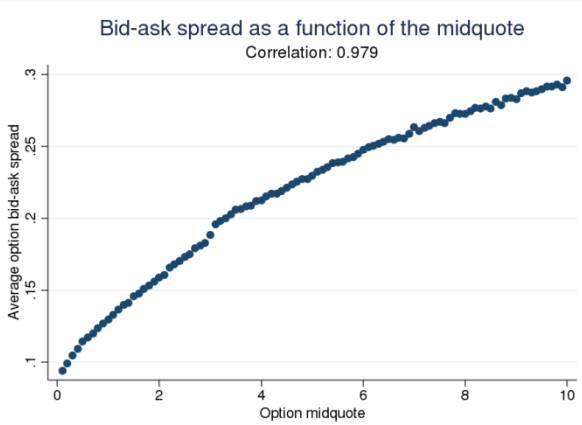
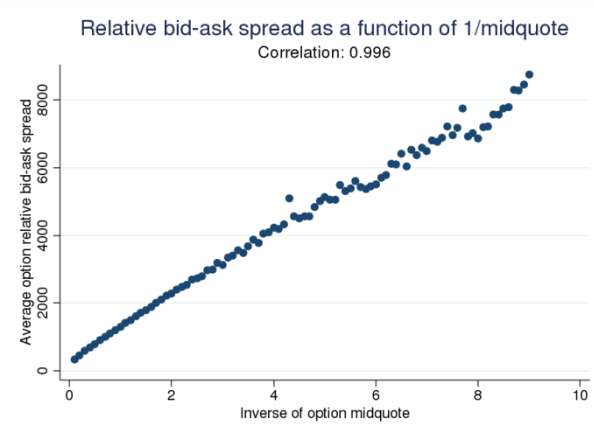


Figure 3: Average option liquidity graphed by transforms of option price and option delta. This figure plots three liquidity metrics averaged in bins of the option price and option delta. *Bid-ask spread* is the average difference between ask and bid; *relative bid-ask spread* is the same divided by the midquote expressed in basis points. *Depth* is the cumulation of the size of outstanding limit orders 25 cents from the option midquote.

Panel A



Panel B



Panel C

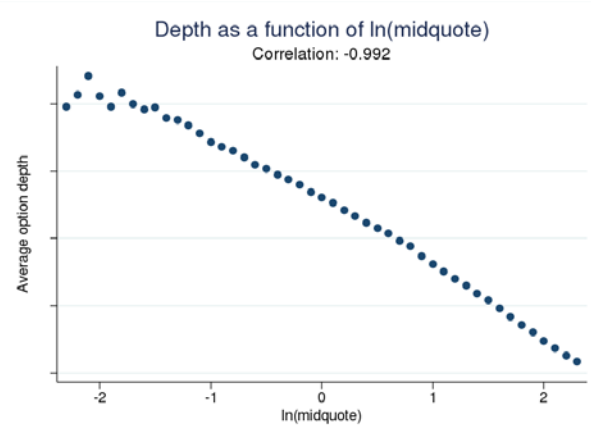


Table 1: Decimalization dates for MX options underlying. These tables give the tickers, underlying company or index, and underlying names of the securities for which the MX decimalized the options. The table also reports whether the ticker was at the time a member of the TSX S&P 60 index or an ETF. There were six decimalization events. Our data sample from 2008 to 2010 covers the latter five.

Ticker	Company	TSX60
27 July 2007		
ABX	Barrick Gold Corp.	Y
BBD	Bombardier Inc.	Y
BCE	BCE Inc.	Y
ECA	EnCana Corp.	Y
NT	Nortel Networks Corp.	Y
RIM	Research In Motion Ltd.	Y
RON	Rona Inc.	N
SLF	Sun Life Financial Inc.	Y
TCK	Teck Cominco Ltd.	Y
XIU	iShares CDN S&P/TSX 60 Index	ETF
25 Jan. 2010		
AEM	Agnico-Eagle Mines Ltd.	Y
BAM.A	Brookfield Asset Management Inc.	Y
BPO	Brookfield Properties Corp.	N
CCO	Cameco Corp.	Y
CNQ	Canadian Natural Resources	Y
ELD	Eldorado Gold Corp.	Y
G	Goldcorp Inc.	Y
IMG	Iamgold Corp.	Y
NXY	Nexen Inc.	Y
SLW	Silver Wheaton Corp.	Y
TLM	Talisman Energy Inc.	N
TCM	Thompson Creek Metals Company Inc.	N
TD	Toronto-Dominion Bank	Y
TRP	TransCanada Corp.	Y
UUU	Uranium One Inc.	Y
YRI	Yamana Gold Inc.	Y
12 July 2010		
ANV	Allied Nevada Gold Corp.	N
ARZ	Aurizon Mines Ltd.	N
CAE	CAE Inc.	N
CVE	Cenovus Energy Inc.	Y
DWI	DragonWave Inc.	N
GIL	Gildan Activewear Inc.	Y
BIN	IESI-BFC Ltd.	N
IVN	Ivanhoe Mines Ltd.	N
MFL	Minefinders Corp. Ltd.	N
NGD	New Gold Inc.	N
SJR.B	Shaw Communications Inc.	Y
SSO	Silver Standard Resources Inc.	N
SXC	SXC Health Solutions Corp.	N
TKO	Taseko Mines Ltd.	N
THI	Tim Hortons	Y
TA	TransAlta Corporation	Y

Ticker	Company	TSX60
21 July 2008		
AGU	Agrium Inc.	Y
BMO	Bank of Montreal	Y
BNS	Bank of Nova Scotia	Y
CM	Canadian Imperial Bank of Commerce	Y
K	Kinross Gold Corp.	Y
MFC	Manulife Financial Corp.	Y
RY	Royal Bank of Canada	Y
SU	Suncor Energy Inc.	Y
TIM	Timminco Ltd.	N
XFN	iShares CDN S&P/TSX Capped Financials In.	ETF
12 Apr. 2010		
BVF	Biovail Corp.	N
CLS	Celestica Inc.	Y
CNR	Canadian National Railway Company	Y
CP	Canadian Pacific Railway Ltd.	Y
ENB	Enbridge Inc.	Y
GAM	Gammon Gold Inc.	N
GNA	Gerdau AmeriSteel Corp.	N
IMO	Imperial Oil Ltd.	Y
MX	Methanex Corp.	N
NA	National Bank of Canada	Y
OTC	Open Text Corp.	N
PAA	Pan American Silver Corp.	N
RCI.B	Rogers Communications Inc.	Y
T	TELUS Corp.	Y
TRI	Thomson Reuters Corp.	Y
4 Oct. 2010		
AAV	Advantage Oil & Gas Ltd.	N
BCB	Cott Corp.	Y
CDM	Coeur d'Alene Mines Corp.	N
FRG	Fronteer Development Group Inc.	N
GIB.A	CGI Inc.	N
GTE	Gran Tierra Energy Inc.	N
HW	Harry Winston Diamond Corp.	N
IMX	IMAX Corp.	N
JAG	Jaguar Mining Inc.	N
MDS	MDS Inc.	Y
PD	Precision Drilling Trust	N
QLT	QLT Inc.	N
SW	Sierra Wireless Inc.	N
SVM	Silvercorp Metals Inc.	N
XEG	iShares S&P/TSX Capped Energy Index	ETF
XGD	iShares S&P/TSX Global Gold Index	ETF

Table 2: Summary statistics on MX options 2008-2010. This table gives sample-wide averages of the daily metrics used in this paper. The averages are taken over all options and reported in six bins by option type and moneyness. Moneyness is defined by the option's Black-Scholes delta: 1/8 to 3/8 is OTM, 3/8 to 5/8 is ATM, and 5/8 to 7/8 is ITM. The *number of trades* is the number of transactions on a date; *trading volume* is the quantity of the transactions. *Bid-ask spread* is the difference between best bid and offer; *effective spread* is the difference between trade price and prevailing midquote signed by initiator of trade; *price impact* is the difference between midquote at trade time and midquote in 30 seconds signed by initiator of trade. Each spread metric is expressed in dollar units and in units relative to the midquote (basis points). The effective spread and price impact are expressed in both their trade-weighted and volume-weighted forms. *Kyle's lambda* is the regression coefficient of the log 30-second return after a trade on the dollar value of the trade signed by initiator of trade. *Inside depth* is the cumulation of limit-order size in a price window some cents within the prevailing bid and best offer. *Intraday return volatility* is the standard deviation of the log return at some frequency. *Intraday return autocorrelation* is the correlation of the log return and lagged log return at some frequency. The *variance ratio* is the absolute value of one minus the one-minute volatility divided by four times the 15-second volatility. *Implied volatility* is the stock volatility implied by an option's terms and price, given by Black-Scholes.

	Puts			Calls		
Daily average	OTM	ATM	ITM	OTM	ATM	ITM
Price	$1.63	$3.46	$4.58	$0.92	$2.57	$2.94
Number of trades	387.3	365.6	113.5	797.8	1139.9	523.4
Trading volume	6934.7	7031.9	1906.5	14609.2	20611.3	9320.6
Bid-ask spread	17.4¢	21.6¢	25.2¢	15.6¢	20.1¢	20.8¢
Relative bid-ask spread	1868.9	850.4	626.6	3164.1	1182.4	1393.1
Effective spread	8.6¢	10.5¢	13.1¢	8.4¢	10.7¢	10.7¢
Relative effective spread	819.8	493.0	368.1	1430.9	621.5	684.9
VW effective spread	8.3¢	10.1¢	12.5¢	8.2¢	10.4¢	10.3¢
VW rel. effective spread	813.5	488.9	363.6	1409.9	612.4	676.4
Price impact	2.5¢	3.4¢	3.6¢	2.2¢	3.3¢	3.3¢
Relative price impact	214.5	177.8	24.3	366.2	198.0	186.1
VW price impact	2.5¢	3.3¢	3.4¢	2.2¢	3.3¢	3.2¢
VW rel. price impact	212.9	173.9	26.0	367.3	199.0	185.9
Kyle's lambda	0.10	0.09	0.06	0.12	0.10	0.09
Intraday return volatility (15s)	0.71	1.20	1.60	0.62	1.07	1.13
Intraday return volatility (1m)	1.26	2.20	2.93	1.11	1.96	2.06
Intraday return autocorrelation (15s)	0.101	0.100	0.102	0.101	0.098	0.100
Intraday return autocorrelation (1m)	0.128	0.115	0.119	0.133	0.114	0.121
Variance ratio (1m to 15s)	0.55	0.54	0.54	0.55	0.54	0.54
Implied volatility	42.5	40.1	40.1	49.9	42.2	42.6
N	30,805	31,412	32,624	32,763	31,487	30,787

Table 3: Estimated treatment effects of options decimalization on spread and depth metrics. This table reports treatment coefficients from a differences-in-differences regression of options liquidity metrics on an after-treatment dummy, a fixed effect for the underlying, and two controls for price effects. The independent variable is the difference of the metric's daily average for treatment options by underlying and the daily average for control options for the same underlying. The regression is run once for each options type-moneyness group. The sample window is two months around the five event dates.

There are three spread metrics: *bid-ask spread* is the difference between best bid and offer prices; *effective spread* is the difference between trade price and prevailing midquote signed by initiator of trade; *price impact* is the difference between the midquote at trade time and the midquote in 30 seconds signed by initiator of trade. Each spread metric is expressed in both dollar units and relative units (basis points) to the midquote. The effective spread and price impact are expressed again in both their trade-weighted and volume-weighted forms. A form of price impact, *Kyle's lambda*, is the regression coefficient of the log 30-second return after a trade on the dollar value of the trade signed by initiator of trade.

Standard errors are clustered by underlying. To economize, we report only the differenced-difference and the average R^2 for the regressions over the type-moneyness groups. Stars indicate the level of statistical significance: one star for 10 per cent, two for 5 per cent, and three for 1 per cent.

	Puts			Calls			Avg.
	OTM	ATM	ITM	OTM	ATM	ITM	R^2
Bid-ask spread	-1.9¢***	-1.9¢***	-1. 6¢***	-1.7¢***	-1.8¢***	-1.9¢***	0.54
Rel. bid-ask spread	-468.1***	-197.1***	-98.0***	-431.1***	-282.8***	-125.5***	0.82
N	2000	2000	1843	2055	1976	1811	
Effective spread	-3.7¢***	-2.0¢**	-2.6¢*	-2.2¢***	-1.9¢***	-2.7¢***	0.15
Rel. eff. spread	-389.4***	-174.6***	-121.5**	-484.1***	-195.5***	-121.9***	0.30
VW effective spread	-3.2¢***	-1.6¢*	-1.3¢	-2.2¢***	-1.8¢**	-1.9¢*	0.13
VW rel. eff. spread	-438.3***	-174.6***	-82.3**	-605.3***	-247.3***	-109.0***	0.29
N	649	569	211	715	724	391	
Price impact	0.3¢	-0.5¢	-1.1¢	-0.2¢	-0.2¢	-0.7¢	0.10
Rel. price impact	-65.6	-64.5**	-26.5	-104.0***	-47.3***	-69.7	0.19
VW price impact	0.4¢	-0.3¢	-0.6¢	-0.0¢	-0.0¢	-0.6¢	0.11
VW rel. p. impact	-74.7*	-62.6**	-11.6	-129.8***	-69.3***	-62.1	0.19
Kyle's lambda	-0.047*	-0.044**	-0.013	0.011	0.004	0.006	0.32
N	650	571	212	716	724	392	

Table 4: Differences-in-differences event studies of decimalization on intraday return volatility and price-efficiency metrics. This table reports treatment coefficients from a differences-in-differences regression of options metrics on an after-treatment dummy, a fixed effect for the underlying, and two controls for price effects. The independent variable is the difference of the metric's daily average for treatment options by underlying and the daily average for control options for the same underlying. The regression is run once for each options type-moneyness group. The sample window is two months around the five event dates.

Inside depth is the cumulation of limit-order size in a price window some cents at and within the prevailing bid and best offer. The case of the inside depth 5 cents to 20 cents is the cumulation to 20 cents within the prevailing bid and best offer minus the same cumulation to five cents. *Depth from the midquote (50 cents*) is the cumulation of limit-order size in a price window 50 cents from the prevailing midquote (rather than within the bid and best offer).

Intraday return volatility is the standard deviation of the log return at some frequency intraday. *Intraday return autocorrelation* is the correlation of the log return and lagged log return at some frequency intraday. The *variance ratio* is the absolute value of the ratio of the one-minute volatility with four times the 15-second volatility minus one.

Standard errors are clustered by underlying. To economize, we report only the differenced-difference and the average R^2 for the regressions over the type-moneyness groups. Stars indicate the level of statistical significance: one star for 10 per cent, two for 5 per cent, and three for 1 per cent.

	Puts			Calls			Avg.
	OTM	ATM	ITM	OTM	ATM	ITM	R^2
Inside depth (0¢)	-5.9	-5.5	-4.7	-8.9***	-9.5***	-7.5*	0.40
Inside depth to 5¢	11.1**	12.2***	7.3	5.1	7.3*	7.3	0.59
Inside depth to 20¢	4.1	7.6***	4.5	0.7	2.5	3.2	0.65
Inside depth, 5¢–20¢	-7.0**	-4.6*	-2.9	-4.4*	-4.8*	-4.2	0.37
Depth, f. mid. to 50¢	-4.3*	-2.6	-3.6	-11.5***	-6.5**	-4.6	0.64
N	2000	2000	1843	2055	1976	1811	
Ret. volatility (15s)	-0.184***	-0.211***	-0.172***	-0.183***	-0.217***	-0.182***	0.60
Ret. volatility (1m)	-0.293***	-0.310***	-0.260***	-0.289***	-0.312***	-0.273***	0.63
Ret. autocorr. (15s)	-0.006	-0.006	-0.004	-0.009**	-0.016***	-0.005	0.23
Ret. autocorr. (1m)	-0.024***	-0.027***	-0.019***	-0.022***	-0.031***	-0.026***	0.21
Variance ratio	-0.011**	-0.022***	-0.019***	-0.012***	-0.023***	-0.021***	0.24
N	1997	2000	1843	2053	1975	1811	

Table 5: Differences-in-differences event studies sorted by underlying option price, volatility, number of trades and underlying bid-ask spread. This table reports treatment coefficients from a differences-in-differences regression of options liquidity metrics on an after-treatment dummy, a fixed effect for the underlying, and two controls for price effects. The independent variable is the difference of the metric's daily average for treatment options by underlying and the daily average for control options for the same underlying. The sample window is two months around the five event dates.

The panels give treatment coefficients for three terciles of an options variable: Panel A, the options price; Panel B, the underlying 30-day realized volatility (taken from Bloomberg); Panel C, the number of trades per day; and Panel D, the option's underlying's relative bid-ask spread.

Standard errors are clustered by underlying. To economize, we report only the differenced-difference and the average R^2 for all the regressions for the metric. Stars indicate the level of statistical significance: one star for 10 per cent, two for 5 per cent, and three for 1 per cent.

Panel A: The impact of decimalization sorted by option price terciles

	$0.10-$1		$1-$2		$2-$3		Avg.
	Puts	Calls	Puts	Calls	Puts	Calls	R^2
Bid-ask spread	-1.7¢***	-1.7¢***	-1.9¢***	-1.8¢***	-1.6¢**	-1.9¢***	0.52
Rel. bid-ask spread	-436.3***	-471.9***	-178.3***	-152.0***	-81.7***	-105.4***	0.70
Inside depth to 5¢	8.6*	6.0	14.4**	7.1	3.7	4.4	0.56
Inside depth to 20¢	4.5	2.7	7.3*	0.2	2.4	2.6	0.61
N	2082	2719	2573	2148	1188	975	

Panel B: The impact of decimalization sorted by underlying volatility terciles

	0<σ<20		20<σ<40		40<σ<100		Avg.
	Puts	Calls	Puts	Calls	Puts	Calls	R^2
Bid-ask spread	-1.6¢*	-1.8¢**	-2.1¢***	-1.9¢***	-1.3¢	-1.6¢	0.53
Rel. bid-ask spread	-274.0***	-369.0***	-251.9***	-230.2***	-219.8***	-345.2***	0.80
Inside depth to 5¢	-0.8	-3.8	18.8*	15.4*	8.5***	2.5	0.52
Inside depth to 20¢	-5.4	-7.7	12.5**	10.4**	6.1**	-1.0	0.54
N	1509	1539	2593	2605	1735	1689	

Panel C: The impact of decimalization sorted by number of trades terciles

	0-1 trades a day		1-5 trades a day		5+ trades a day		Avg.
	Puts	Calls	Puts	Calls	Puts	Calls	R^2
Bid-ask spread	-1.2¢***	-1.1¢***	-2.6¢***	-1.8¢***	-1.6¢*	-2.2¢***	0.55
Rel. bid-ask spread	-189.9***	-253.6***	-336.8***	-387.3***	-237.4***	-252.8***	0.81
Inside depth to 5¢	2.4	5.0	17.8**	5.9	15.3**	7.8*	0.54
Inside depth to 20¢	2.3	5.6	10.2**	2.0	4.7	0.6	0.57
N	2638	1202	2076	2239	1129	2401	

Panel D: The impact of decimalization sorted by the underlying stock liquidity terciles

	1-25bps spread		25-50bps spread		50-100bps spread		Avg.
	Puts	Calls	Puts	Calls	Puts	Calls	R^2
Bid-ask spread	-1.2¢	-1.3¢	-2.6¢***	-2.4¢***	-1.3¢	-1.5¢**	0.53
Rel. bid-ask spread	-240.7***	-114.5	-282.6***	-371.0***	-227.8**	-390.8***	0.80
Inside depth to 5¢	3.6	-1.7	13.1**	8.5*	20.0	18.6	0.56
Inside depth to 20¢	-3.8	-7.5*	11.8***	5.0**	11.9	13.5	0.59
N	1997	1973	2217	2232	1230	1199	

Table 6: Cross-sectional regression of the treatment effect on options liquidity determinants. This table reports the results of a linear regression of treatment effects of decimalization on options liquidity variables. The treatment effects are collected from a differences-in-differences regression of three liquidity metrics on an after-treatment dummy, a fixed effect for the underlying, and two controls for price effects. The independent variable is the difference of the metric's daily average for treatment options by underlying and the daily average for control options for the same underlying. The sample window is two months around the five event dates. The model is fit once by underlying-type-moneyness and the treatment effects are collected.

The regression attempts to explain the treatment effect on the relative bid-ask spread in column 1, the inside depth to five cents in column 2, and the inside depth to 20 cents in column 3. The explanatory variables are the pre-period averages during the month before decimalization of the four metrics as well as the control variates for price effects used in the paper, the option price and the log of the absolute value of the option delta.

	(1) Treatment effect, relative bid-ask spread	(2) Treatment effect, inside depth to 5¢	(3) Treatment effect, inside depth to 20¢
Pre-period average	8.83		
bid-ask spread	(1.56)		
Pre-period average	-0.08***		
rel. bid-ask spread	(-3.19)		
Pre-period average		0.24***	0.77***
inside depth to 5¢		(4.90)	(5.36)
Pre-period average			-0.58***
inside depth to 20¢			(-5.24)
Pre-period average	116.43***	-2.01	-1.09
option price	(2.61)	(-0.81)	(-0.49)
Pre-period average	122.59**	1.17	2.88
ln. option delta	(2.22)	(0.32)	(0.88)
Constant	-197.94*	7.01	9.42*
	(-1.92)	(1.22)	(1.85)
Stock FE	Yes	Yes	Yes
N	311	311	311
R^2	0.368	0.074	0.089