Intermediary Option Pricing*

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Abstract

I find that the option risk premium compensates option market makers for equity market inventory risk, which emerges when equity illiquidity impedes continuous delta-hedging. Using positions data, I quantify this intermediary risk, which is missed by common (gamma) measures. Exploiting the mid-2000s expansion of overnight equity trading, I show that greater overnight equity liquidity reduces the option risk premium, with intra-week option returns becoming less negative than weekend returns, particularly in options that appear in intermediaries inventory, pointing to a causal effect of intermediary inventory risk on the option risk premium.

Keywords: Asset Pricing, Derivatives, Intermediation, Inventory Risk, Liquidity

JEL Codes: G10, G12, G13, G14

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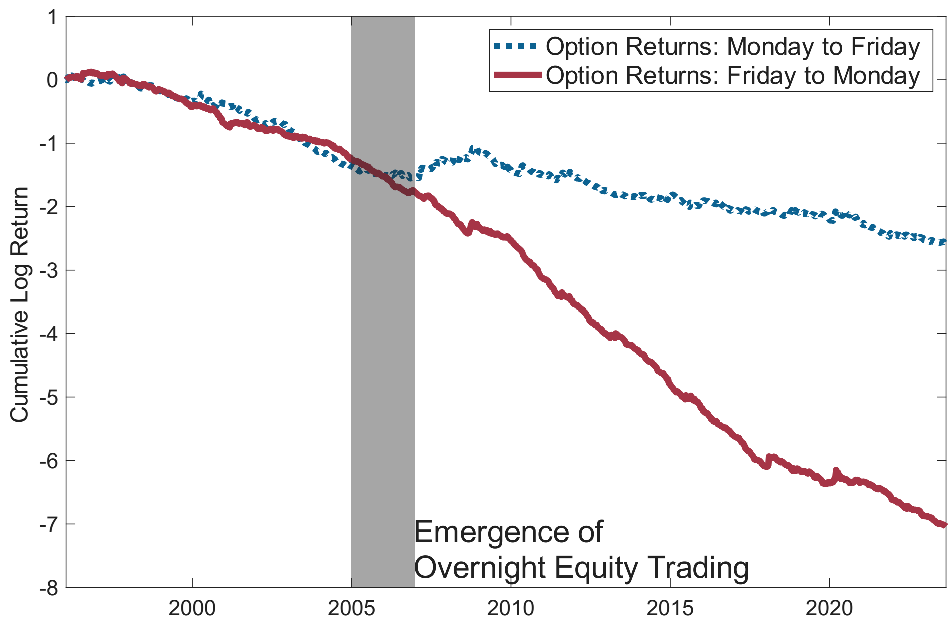
Average delta-hedged returns on S&P 500 options are about –0.5% per day. These returns arise in a market that has grown rapidly: between 2018 and 2023, open interest and trading volume in S&P 500 options nearly quadrupled, reaching $250 billion and $2 trillion per year, respectively.[1] Yet, option returns remain puzzling. Jones and Shemesh (2018) and Muravyev and Ni (2020) show that option losses are concentrated over weekends and nights, and they conclude that neither increased volatility risk nor increased jump risk can explain this pattern. Bates (2022) notes that the role of intermediary constraints in shaping option returns remains unresolved. This paper empirically links the overnight option risk premium to intermediaries' unhedgeable inventory risk.

To identify the relevant hedging friction, the analysis exploits the sharp rise in overnight equity trading around 2006 to study how equity market liquidity affects the option risk premium. A liquid equity market is essential for delta-hedging, that is, for the continuous rebalancing of stock positions that offsets an option's exposure to underlying price changes, a cornerstone of modern option pricing since Black and Scholes (1973) and Merton (1973). The mid-2000s expansion of overnight trading provides a natural experiment: equity trading activity increased substantially during weeknights but remained negligible over weekends. This setting allows for a clean comparison of option returns over otherwise similar periods that differ only in overnight stock liquidity. I find that option returns within the week (Monday close to Friday close) became significantly less negative after the emergence of overnight equity trading, relative to weekend returns (Friday close to Monday close). Figure 1 illustrates this result, which is strongest for short-dated, out-of-the-money puts, precisely where intermediaries' short exposures and hedging constraints are most pronounced.

I use detailed position data to explain *why* equity liquidity affects the option risk premium. For each day between 2011 and 2023, I estimate dealers' aggregate positions across all outstanding S&P 500 index options. The data reveal a persistent short position in deep out-of-the-money puts, exposing intermediaries to large losses in market downturns. Using these positions, I simulate dealers' profit and loss under hypothetical S&P 500 returns, assuming that illiquid overnight markets prevent timely hedge adjustments. A 10% decline in the S&P 500 would generate losses of roughly twice the value of dealers' option inventories unless deltas are rebalanced. Maintaining full delta-hedges would require equity sales of about $8 billion—far exceeding typical overnight

[1] For early studies on option returns, see Coval and Shumway (2001) and Bakshi and Kapadia (2003).

Figure 1: Increasing Equity Trade Volume Lowers the Option Risk Premium



Note: This figure shows cumulative log returns of S&P 500 put options. The dotted line cumulates returns from Monday to Friday, the solid line cumulates returns from Friday to Monday. Returns are measured between trading days' market close at 16:15 (E.T.) and delta-hedged at the daily close. The Monday to Friday return is the average over the four returns between Monday close and Friday close. Returns are in logs and are scaled to the same 10% annualized volatility. The vertical line indicates the emergence of overnight equity trading around 2006.01.

trading volumes. For reference, the most liquid S&P 500 futures contract (the E-Mini) trades well below \$1 billion per hour during most night-time hours. I conclude that dealers bear substantial overnight equity market risk because the hedge adjustments needed to eliminate it are prohibitively costly. By contrast, during regular trading hours,when both futures and equities are highly liquid, dealers face little such exposure.

The evidence supports an inventory-risk explanation in which negative option returns compensate intermediaries for bearing unhedgeable exposure. Investors exhibit a positive net demand for crash protection—especially short-dated, out-of-the-money puts—as portfolio insurance.[2] Market makers supply these contracts only at prices that embed compensation for overnight exposure, when delta-hedges cannot be maintained. Accordingly, delta-hedged option returns are negative on average, concentrated overnight and over weekends, and most pronounced in puts, consistent with dealers' downside-skewed inventories.

[2]I measure market makers' option inventory and the resulting inventory risk, but I remain agnostic about the underlying drivers of investors' option demand.

This perspective sharpens existing evidence on option premia and intermediary inventory. Bollen and Whaley (2004) and Garleanu, Pedersen, and Poteshman (2009) relate option prices to dealers' exposure to jump and volatility risk and document positive correlations between inventory and prices, whereas Chen, Joslin, and Ni (2019) find negative correlations in a later sample. Because intermediary asset-pricing models can rationalize both signs, correlation tests alone are not decisive. I show instead that the premium materializes precisely when hedging constraints bind (overnight) and where dealers' short exposure is concentrated (puts). The identification logic parallels Du, Tepper, and Verdelhan (2018), who document that CIP deviations spike when bank balance-sheet constraints tighten at quarter-ends, and are largest in instruments that load most on those constraints.

The results also have market-design implications. In late 2024 and early 2025, NYSE and Nasdaq announced plans to extend weekday equity trading toward a near 24-hour schedule.[3] My evidence implies that greater overnight equity liquidity should ease dealers' inventory risk and compress option risk premia, thereby lowering the cost of crash insurance borne by end investors.

The first part of the paper documents the mid-2000s rise in week-night equity trading. Regulation NMS and the exchanges' acquisition of major ECNs expanded overnight activity Monday–Friday, while weekends remained largely shut. This discontinuity yields a clean design: intra-week close-to-close option returns (Monday–Friday) are the treated group, and weekend returns (Friday–Monday) are the control.[4] Around 2006, treated returns become markedly less negative relative to controls; the divergence is large and persistent for S&P 500 puts (Figure 1). This timing complements Dew-Becker and Giglio (2023), who find a break in the volatility risk premium around the same time, and points to overnight equity liquidity as the mechanism.

To explain why liquidity matters, I estimate dealers' aggregate positions using CBOE data (2011–2023). Intermediaries hold a persistent net short in puts (about 19 million contracts) while call positions hover near zero. Given this imbalance, a large overnight decline exposes dealers to losses unless hedges are rebalanced in thin markets. Under a hypothetical 10% S&P 500 move, simulated losses are roughly 200% of inventory value absent re-hedging, and maintaining

[3] https://ir.theice.com/press/news-details/2024/The-New-York-Stock-Exchange-Plans-to-Extend-Weekday-Trading-on-its-NYSE-Arca-Equities-Exchange-to-22-Hours-a-Day/default.aspx, accessed on November 01, 2024. https://www.reuters.com/markets/us/nasdaq-plans-24-hour-trading-tap-into-growing-international-demand-2025-03-07/, accessed on March 17, 2025.

[4] I do not compare overnight to intraday returns around 2006 due to the lack of liquid high-frequency option prices at that time.

delta-neutrality requires multi-billion-dollar equity sales. Typical overnight E-mini turnover is well below \$1 billion per hour, versus more than \$20 billion per hour intraday (plus roughly \$27 billion per hour in underlying stocks), making continuous re-hedging infeasible overnight and creating equity market risk.

Standard risk measures miss this exposure. Aggregate dealer inventory gamma is near zero or slightly positive, indicating that the dealer option portfolio experiences gains from small equity price moves. However, re-calculating dealer inventory gamma for the scenario where the S&P 500 has fallen by, for example, 10%, reveals a large negative aggregate dealer inventory gamma. I refer to such scenario gamma as ”shadow gamma”. Shadow gamma captures dealers exposure to large equity price moves over (night) periods, where the delta-hedge adjustments are prohibitively expensive. Option dealer shadow gamma predicts option returns, particularly in out-of-the-money puts, where shadow gamma is concentrated.

Contributions. This paper contributes to the literature on option returns. Black and Scholes (1973) and Merton (1973) establish the risk-free rate as the benchmark for delta-hedged option returns. Coval and Shumway (2001) and Bakshi and Kapadia (2003) show that delta-hedged returns of equity index options are negative, especially for puts. Jones and Shemesh (2018) and Muravyev (2016) show that option returns are especially negative over weekends and nights, and provide explanations based on market mispricing. Jones and Shemesh (2018) show that weekend returns could be explained if investors systematically underestimate the time decay in the option value over weekends. Muravyev and Ni (2020) show that night returns could be explained if investors systematically overestimate overnight equity volatility. I show that intermediaries' exposure to overnight equity market risk can explain negative option returns.

This paper contributes to the literature on liquidity premia in options markets. Cao and Han (2013) and Kanne, Korn, and Uhrig-Homburg (2023) show that stock option risk premia decrease in the liquidity of the underlying stocks. Christoffersen, Feunou, Jeon, and Ornthanalai (2021) estimate a model where the crash probability of the S&P 500 depends on its liquidity. To the best of my knowledge, this is the first paper to provide evidence in support of a causal impact of market liquidity on asset risk premia. I find that it is the *overnight* il-liquidity of stocks that drives S&P 500 option returns, because of intermediaries inventory risk.

Finally, this paper contributes to the literature on intermediary asset pricing. Haddad and

Muir (2021) and He, Kelly, and Manela (2017) show that intermediary constraints can explain variation in returns across many asset classes. Bollen and Whaley (2004) and Garleanu, Pedersen, and Poteshman (2009) provide evidence that intermediaries' inventory risk can account for some of the risk premium in options. Du, Tepper, and Verdelhan (2018) show increased cip deviations around quarter-ends, when banks face tighter capital requirements. I link the day night variation in the option risk premium to intermediary constraints.

I. Markets and Data

This section outlines the market for S&P 500 options, stocks and futures, which are the focus of this paper. The section briefly states data sources, while details on variable construction are in the respective sections.

S&P 500 Options. This paper studies S&P 500 equity index options (SPX options), i.e., put- and call options written on the S&P 500 equity index of U.S. large-cap stocks. SPX options are exchange-traded exclusively on the Chicago Board Options Exchange (CBOE) and were initially listed in 1983. While SPX option volumes were initially small, volumes have grown to about \$2tn a year in 2023 and open interest has grown to about \$250bn. The SPX options market is the worlds' largest and most liquid equity options market. The high option liquidity enables a return decomposition at high frequency and the large market size makes SPX options an economically relevant market to study.

The original SPX options expired once a month on that months' 3^{rd} Friday. Recently, the CBOE has successively added SPXW options with different expiry dates.[5] I include both SPX and SPXW options into the analysis of this paper and refer to both jointly as SPX options or S&P 500 options. SPX options are liquid across a broad range of strike prices, which occur every \$5. Liquidity is particularly high for out-of-the-money options, which are puts (calls) with strike prices below (above) the current value of the underlying index. SPX options are European, which can only be exercises at expiry.

A major advantage of the S&P 500 index options market for the study of intermediary asset pricing is the availability of comprehensive trade data. S&P 500 index options trade exclusively

[5]Specifically, the CBOE added weekly Friday expiries in 2011.09, Wednesday expiries in 2016.02, Monday expiries in 2016.08, Tuesday expiries in 2022.04, and Thursday expiries in 2022.05.

on the Chicago Board Options Exchange (CBOE) and the CBOE makes datasets commercially available that allow for the daily measurement of the options position of the intermediary sector. Intermediaries' options position provide information on their risk exposures and risk management.

S&P 500 Stocks, Futures and ETFs. The most important delta hedging instruments for S&P 500 options are the underlying stocks, as well as associated Futures and ETFs. S&P 500 constituent stocks and SPY (the S&P 500 exchange-traded fund) trade on U.S. exchanges (NYSE, Nasdaq). Regular exchange hours are 09:30–16:00 (E.T.); by the mid-2000s, exchanges expanded extended hours to 04:00–20:00, yet there is little equity trading from 20:00 to 04:00. Pre-market activity is thin (about 0.27% of S&P 500 stock volume) and post-market thinner still (about 0.12%), and intraday equity volumes follow a U-shape, with weekend trading closed entirely. ETFs share the same venues and hours as their underlying stocks. S&P 500 exposure via futures is provided by the CME's E-mini contract on Globex, which trades nearly 24/5, from Sunday 18:00 to Friday 17:00 with a daily 17:00–18:00 maintenance break; E-mini trading supplanted the standard pit-traded contract over time. Volumes differ starkly between day and night: average intraday E-mini dollar volume (2011–2022) is about $164 bn per day versus only about $7bn overnight (a day to night ratio near 25:1), and at higher frequency, intraday futures turnover runs roughly $8–$15bn per 30-minute window compared with about $250m per 30-minute window overnight. Consistent with this, aggregate equity volumes rose from roughly $20bn per day in the late 1990s to about $200bn per day after 2020, but remain small in the pre- and post-market windows. The online appendix contains tables and figures on equity returns and volumes over day and night periods.

Data Sources. From CBOE, I obtain SPX option prices and quotes at 15-minute intervals. Further, I obtain the daily "Open Close Volume" files that allow for the construction of intermediary positions. From OptionMetrics, I obtain SPX option prices and quotes at the daily frequency. I obtain data on S&P 500 E-mini futures from Boyarchenko, Larsen, and Whelan (2023), who sample tick-level data of CME traded futures contracts. I obtain data on risk-free rates from the OptionMetrics IvyDB zero-curve file. Data on daily stock trading volume is from CRSP. High-frequency stock volumes are from Reuters. From Eikon, I obtain tick level data on S&P 500 E-mini futures traded on the CME, comprising best bid offers, trade prices, and volumes.

Details on variable construction are in the respective sections.

II. Causal Evidence on Equity Liquidity and the Option Risk Premium

This section exploits the sharp increase in overnight equity trading around 2006 to study how overnight equity liquidity affects the option risk premium. Substantial weeknight trading activity emerged only after Nasdaq and NYSE acquired major electronic communication networks, marking a structural shift in market design. This institutional change provides a natural experiment for a difference-in-differences estimation: option returns realized within the week (Monday to Friday) serve as the treated group, and weekend returns (Friday to Monday) as the control.

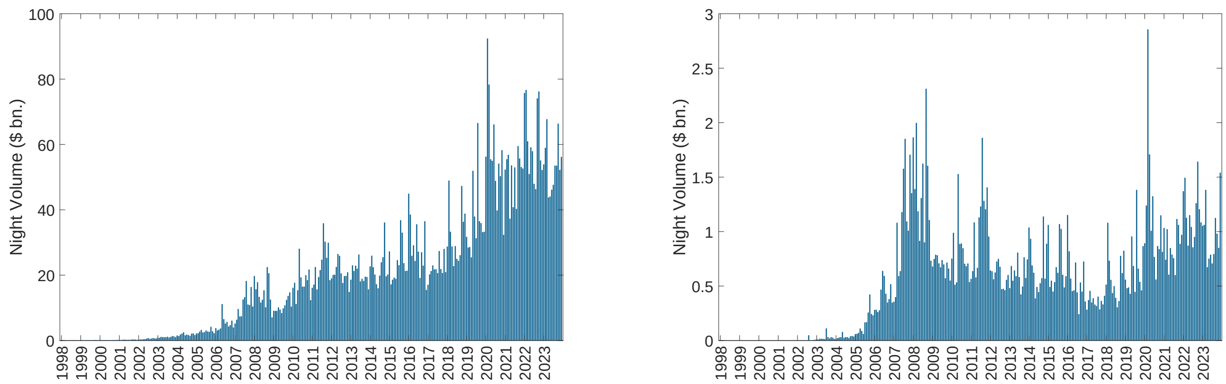
I show that following the emergence of overnight equity trading, intra-week option returns become substantially less negative relative to weekend returns. The effect is concentrated in out-of-the-money put options, where market-makers' inventory risk is most pronounced. These results suggest a causal link between equity market liquidity and the option risk premium, operating through intermediaries' ability to manage inventory risk when underlying equities are tradable overnight.

II.A. The Emergence of Overnight Equity Trading

The institutional foundations of overnight equity trading developed gradually, but the key structural changes can be traced to the mid-2000s. In the early 1990s, the New York Stock Exchange (NYSE) began limited off-hours trading sessions, and by the late 1990s, regulatory and technological innovations accelerated the transition toward electronic markets. Regulation ATS (Alternative Trading Systems) of 1998 formally distinguished ATSs from registered exchanges and heightened transparency requirements, prompting several electronic communication networks (ECNs) to consolidate and register as full exchanges.

A sequence of mergers and technological upgrades followed. In 2001, Archipelago ECN merged with the Pacific Exchange to form ArcaEx, the first fully electronic stock exchange. In 2005, the NYSE launched its Hybrid Market, combining electronic order matching with traditional floor trading, and one year later, after becoming a public company, it acquired Archipelago and phased out the open-outcry system. Around the same time, Nasdaq sought to regain competitiveness

Figure 2: The Emergence of Overnight Equity Trading



(a) S&P 500 Futures

(b) S&P 500 ETF

Note: This figure shows the rise of overnight equity trading activity in S&P 500 instruments. Panel (a) reports the monthly average dollar volume transacted overnight in the most actively traded S&P 500 E-mini futures contract, while Panel (b) shows the corresponding series for the SPY ETF. Overnight trading is defined as transactions between 16:00 and 09:30 (E.T.) and volumes are expressed in billions of dollars.

by acquiring Instinet and, following its 2005 IPO, expanded trading hours from 08:00–18:30 to 04:00–20:00. These reforms were completed by 2006 and established the extended stock trading hours that define modern U.S. equity markets and marked the beginning of meaningful overnight liquidity in large-cap equities.

Meaningful overnight equity trading activity emerged only in the mid-2000s. Although S&P 500 E-mini futures had traded nearly around the clock since their 1996 launch, overnight volumes remained negligible for almost a decade. Figure 2 documents the subsequent take-off in trading activity. Panel (a) plots the monthly average overnight dollar volume in the most actively traded S&P 500 E-mini futures contract, while Panel (b) shows the corresponding series for the SPY ETF. Both series rise sharply beginning around 2006. While overnight ETF volumes are smaller in absolute terms, their emergence indicates that meaningful stock trading had become possible outside regular exchange hours.

The sharp increase in week-night trading, contrasted with persistently closed weekend markets, provides a natural setting to study how equity liquidity affects the option risk premium. Intra-week option returns, which include nights when equity markets are now tradable, serve as the treated group, while weekend returns, which span periods of more than forty-eight hours without equity or futures trading, serve as the control. If higher equity liquidity relaxes dealers' hedging frictions, option returns within the week should become less negative relative to those over weekends following the onset of overnight trading. Because reliable high-frequency option quotes are not vailable before the late 2000s, I implement the test using daily close-to-close data, which allows for consistent measurement of option returns over the full 1996–2023 sample, while avoiding biases from sparse intraday observations.

II.B. Option Returns And Delta-Hedging

Throughout the paper, I calculate delta-hedged option returns as:

$$R_t^i = \frac{P_t^i - P_{t-1}^i \; - \; \Delta_{t-1}^i \; \times \; (SPX_t - SPX_{t-1})}{P_{t-1}^i}, \tag{1}$$

where P_t^i is the option mid-quote at the end of period t, SPX is the S&P 500 level and Δ_{t-1}^i is the lagged option delta. This return removes first-order exposure to the equity risk premium and follows the standard approach in option-pricing studies (for example, Bakshi and Kapadia (2003); Jones and Shemesh (2018)). The implicit assumption that trading the underlying requires no capital is reasonable given the depth of S&P 500 futures during regular hours.

Delta-hedging neutralizes small moves in the underlying but not larger ones: as prices change, deltas change, forcing continuous hedge rebalancing. Because overnight equity trading is thin, intermediaries cannot adjust hedges in real time and therefore remain exposed to large overnight returns. This friction is central to the paper's mechanism: when market liquidity is low, delta-neutrality is only notional, and option sellers carry unhedgeable inventory risk.

Using delta-hedged rather than raw option returns ensures that differences between day and night returns do not merely reflect the positive drift in equities. Throughout, results are robust to alternative delta specifications and to small variations in the return-measurement window.

II.C. Identifying the Effect of Equity Liquidity on Option Returns

Data: Daily Option Returns. OptionMetrics aggregates option trades at the daily frequency, such that all available observations are at 16:00. I obtain option's bid quote, ask quote, and delta. While OptionMetrics applies a proprietary method for calculating options' deltas, their deltas are typically close to Black-Scholes deltas where sigma is set equal to the options implied volatility. To alleviate concerns of liquidity and data errors, I apply several filters to the data. I exclude options

Table I: The Effect of Equity Liquidity on Put Option Returns: Difference-in-Differences

	(1) Baseline	(2) Winsorized	(3) Excl. Crashes
Intra-week	86.7	95.0**	86.7
	(1.42)	(2.08)	(1.42)
Post	-264.5***	-292.5***	-358.0***
	(-3.16)	(-5.75)	(-5.11)
Intra-week x Post	355.8***	304.2***	429.4***
	(4.05)	(5.33)	(5.41)
Constant	-231.4***	-278.8***	-231.4***
	(-4.05)	(-6.89)	(-4.05)
Observations	6,958	6,958	6,812
R2-adjusted	0.01	0.02	0.01

Note: The table shows regression estimates of equation 2, where option returns are regressed on indicators for treated periods (intra-week returns), and the post event period. Option returns are for the portfolio of out-of-the-money S&P 500 puts. Intra-week returns comprise of all daily close-to-close returns, except Friday to Monday. Column (1) presents the baseline regression, column (2) contains option returns winsorized at percentiles 5 and 95, column (3) excludes the crisis months of 2018.02 and 2020.02 to 2020.04. Returns are in basis points and are delta-hedged. Standard errors are clustered within every month. The sample period is 1996 to 2023.

with a zero trade volume on any of the previous three days. I discard options with negative lagged bid-ask spreads, lagged bids of 0, lagged mid quotes below \$0.05 or lagged spreads above \$10. I discard large hedged or un-hedged reversal returns (returns above 1000% immediately followed by −90% or vice versa). Finally, I discard observations that violate no-arbitrage bounds.

To examine how the option risk premium changes with the emergence of overnight equity trading, I estimate the following difference-in-differences specification:

$$R_t^i \;=\; \beta_1 \,\text{Intra-week}_t \;+\; \beta_2 \,\text{Post}_t \;+\; \beta_3 \,\text{Intra-week}_t \;\times\; \text{Post}_t \;+\; \epsilon_t^i, \tag{2}$$

where R_t^i denotes the delta-hedged return of portfolio i of out-of-the-money S&P 500 put options. $IntraWeek_t$ is an indicator for close-to-close returns that fall within the week (i.e., not Friday-to-Monday), and $Post_t$ equals one for observations after January 2006, when meaningful overnight equity trading began. Weekend returns are measured from Friday 16:00 to Monday 16:00, while intra-week returns include all other close-to-close intervals. Standard errors are clustered by month.

Tables I and II report results based on portfolios of options rather than individual contracts. Aggregating options into portfolios mitigates measurement error arising from idiosyncratic pricing noise, thin trading, and bid–ask bounce that affect individual option quotes. Portfolio-level returns smooth out microstructure frictions and ensure that each observation represents a well-diversified position within a given moneyness–maturity bin, which improves comparability across periods and reduces the influence of outliers. This approach follows standard practice in the options literature (e.g., Coval and Shumway (2001); Bakshi, Charles, and Chen (1997)), where portfolios serve as more reliable estimators of systematic return patterns than individual option-level regressions.

Table I reports estimates from Equation 2. In Column (1), the constant (-231.4 bps) indicates that before 2006, average weekend option returns were substantially negative. The coefficient on Post (-264.5 bps) implies that weekend returns became even more negative after the emergence of overnight equity trading, consistent with a general increase in option risk premia during the post-period. In contrast, intra-week returns were moderately less negative before 2006 (-144.7 bps $= -231.4 + 86.7$) and turned nearly flat afterward ($-53.4bps = -231.4 + 86.7 - 264.5 + 355.8$). The interaction term Intra-week $\times$ Post (355.8 bps, $t = 4.05$) provides the key difference-in-differences estimate: option returns within the week became significantly less negative relative to weekend returns once overnight equity trading emerged.

Columns (2) and (3) show that this result is robust to winsorizing returns at the 5th and 95th percentiles and to excluding major crisis months (2018.02 and 2020.02–2020.04). Across specifications, intra-week returns remain consistently higher than weekend returns after 2006. These findings indicate that greater overnight equity liquidity mitigated the negative option risk premium, consistent with the interpretation that improved liquidity relaxes dealers' hedging frictions. When equity trading is limited, intermediaries face higher inventory risk because they cannot continuously adjust their delta-hedges; the increase in overnight liquidity alleviates this constraint.

The rise in the weekend risk premium during the post-period, visible in the second row of Table I, likely reflects the timing of the 2008 Global Financial Crisis, which followed shortly after the onset of overnight equity trading. Risk premia across many asset classes were unusually compressed in the years preceding the crisis and increased sharply thereafter. The more negative weekend returns observed after 2008 therefore may capture a broader repricing of macroeconomic risk and heightened investor demand for crash protection.

Table II: Equity Liquidity and Option Returns: Triple-Difference Estimates

	(1) Baseline	(2) Winsorized	(3) Excl. Crashes
Intra-week	85.7**	115.1***	85.7**
	(2.40)	(4.41)	(2.40)
Post	-84.4**	-98.6***	-154.7***
	(-1.98)	(-3.27)	(-3.89)
Intra-week x Post	121.9***	92.9***	174.2***
	(2.60)	(2.74)	(3.87)
OTM Puts	-307.3***	-350.7***	-307.3***
	(-2.94)	(-5.27)	(-2.94)
Intra-week x OTM Puts	61.7	55.9	61.7
	(0.56)	(0.73)	(0.56)
Post x OTM Puts	-305.6**	-348.1***	-409.7***
	(-1.97)	(-4.13)	(-3.24)
Intra-week x Post x OTM Puts	470.9***	421.3***	561.0***
	(2.93)	(4.38)	(3.97)
Constant	-134.7***	-184.5***	-134.7***
	(-4.21)	(-7.92)	(-4.21)
Observations	54,842	54,842	53,675
R2-adjusted	0.00	0.01	0.01

Note: This table reports estimates from a triple-difference specification based on Equation 2, in which option returns are regressed on indicators for treated options (OTM puts), treated periods (Intra-week), and the post-event period. Option returns are computed for eight out-of-the-money portfolios (four puts and four calls) with breakpoints defined in Table A.6. Intra-week returns include all close-to-close observations except Friday-to-Monday intervals. Column (1) presents the baseline regression; Column (2) uses returns winsorized at the 5th and 95th percentiles; Column (3) excludes the crisis months 2018.02 and 2020.02–2020.04. Returns are expressed in basis points and are delta-hedged. Standard errors are clustered by $month \times portfolio\ ID$. The sample period is 1996 to 2023.

II.D. Enhancing Identification: A Triple-Difference Test

To further isolate the liquidity channel and assess where the effect is most pronounced, I extend the analysis to a triple-difference specification that interacts the treatment with cross-sectional variation in option type. Specifically, I compare out-of-the-money puts, where dealer inventory risk is concentrated, to other option portfolios. This approach sharpens identification and reveals whether the liquidity effect operates primarily through the options that contribute most to intermediaries inventory risk.

Table II extends the baseline difference-in-differences framework of Table I by adding a third dimension of variation across option types. To that end, the table contains option returns for eight out-of-the-money portfolios (four puts and four calls) with breakpoints defined in Table A.6. While the regression in Table I compares Intra-week and weekend option returns before and after the emergence of overnight equity trading, the triple-difference specification exploits cross-sectional heterogeneity between out-of-the-money puts and other option portfolios. This additional layer of identification isolates the liquidity effect from broader time-series shifts in option risk premia by comparing treated and untreated options within the same periods. In doing so, the specification tests whether the impact of overnight equity liquidity is strongest precisely where hedging frictions are expected to bind most tightly and helps rule out confounding explanations driven by aggregate shocks or changes in overall market volatility.

Column (1) shows that the key triple-interaction term, $Intra-weekPostOTMputs$, is large and statistically significant (470.9 bps, $t = 2.93$). This coefficient indicates that the post-2006 improvement in intra-week option returns documented in Table I is concentrated in out-of-the-money puts—the contracts that dominate dealers' short inventory positions and thus carry the highest hedging frictions. The positive estimate implies that overnight equity liquidity reduced the magnitude of negative returns specifically for those options most exposed to dealers' inventory risk. In contrast, the lower-order interactions ($Intra-week \times Post$,$Post \times OTM\ puts$) are smaller in magnitude, confirming that the observed effect is not a broad repricing across all options but rather a targeted easing of the liquidity constraint faced by intermediaries holding downside risk.

Columns (2) and (3) show that the triple-difference results are robust to outliers. Column (2) winsorizes option returns at the 5th and 95th percentiles, while Column (3) excludes the crisis months of 2018.02 and 2020.02–2020.04. Across both specifications, the coefficient on $Intra-week \times Post$,$Post \times OTM\ puts$ remains positive, large, and statistically significant, confirming that the attenuation of the negative option risk premium is not driven by outliers or by periods of exceptional market stress. The persistence of the effect across samples reinforces the interpretation that improved overnight equity liquidity eases dealers' hedging constraints and thereby reduces the compensation investors pay for bearing downside option risk.

A potential concern for identification is that neither "weekend" nor "overnight" periods are completely non-tradable. Pre-market equity trading begins at 04:00 on Monday mornings, and E-mini S&P 500 futures reopen as early as Sunday 18:00. Hence, the weekend control group is only partially untreated. I address this concern in several ways. First, the expansion of equity trading hours around 2006 was far more pronounced for weeknights than for weekends. A typical weeknight spans 17.5 hours (16:00 – 09:30). The introduction of post-market (until 18:00) and pre-market (from 04:00) trading reduced its non-tradable share by roughly 30 percent. By contrast, a weekend period spans about 65.5 hours (17.5 plus 48), for which the same extension lowers non-tradable hours by less than 10 percent. Consistent with this difference, Figure A.4 shows that weeknight trading volumes in futures and ETFs increased much more sharply than weekend volumes. Finally, Table A.2 presents estimates from a continuous-treatment specification that uses measured overnight liquidity instead of the 2006 breakpoint. The results confirm that greater overnight equity liquidity significantly compresses the option risk premium, particularly for deep out-of-the-money puts.

The appendix provides several additional robustness analyses. Figure A.1 shows no evidence of pre-event trends in the weekend or intra-week returns of out-of-the-money puts, supporting the parallel-trend assumption underlying the difference-in-differences design. Table A.1 reports a decline in option bid–ask spreads for intra-week relative to Friday-close observations around 2006, consistent with the notion that market makers' required compensation for providing liquidity fell once overnight equity trading improved. Table A.3 documents a similar pattern in VIX futures: intra-week returns become less negative relative to weekend returns after 2006. The evidence from VIX futures reinforces the main result in a liquid, transparent, and easily replicable return series, underscoring that the effects of improved overnight liquidity extend beyond the option market itself.

III. Intermediaries' Inventory Risk from Equity Illiquidity

Having shown that improved overnight equity liquidity reduces the magnitude of the option risk premium, I next examine the mechanism through which equity market frictions translate into option pricing. This section shows that intermediaries' option inventories expose them to substantial equity market risk over periods when illiquidity prevents timely hedge adjustments. Standard option risk measures, such as gamma, fail to capture this risk.

I begin by exploiting comprehensive CBOE trade data to estimate market makers' aggregate option positions. In call options, intermediaries' buy and sell volumes are roughly balanced, whereas in put options, sell volumes consistently exceed buy volumes. As a result, the intermediary sector holds a persistent net short position in puts, particularly deep out of the money puts. This asymmetric inventory exposes intermediaries to downside equity market risk: a 10% decline in the S&P 500 would imply losses of roughly 200% of their option inventory value in the absence of hedge adjustments. Continuous delta-hedging could offset such losses, but doing so would require selling on the order of $8 billion in equities, which far exceeds overnight trading volumes during most hours of the night.

I then show that conventional risk measures fail to capture this exposure and propose a new measure, shadow gamma, which better reflects intermediaries' sensitivity to large, infrequent equity price moves when markets are illiquid. Finally, I provide evidence that intermediaries actively manage their option positions in response to changing equity market volatility, consistent with behavior aimed at mitigating this equity market risk.

III.A. Intermediaries' Option Position: Short Puts

Data: Option Trade Volume by Trader Type. I use the CBOE Open–Close Volume files, which report daily option volumes by contract (put or call, strike, and maturity), trader group (market maker, broker-dealer, firm, customer, and professional customer), and trade direction (buy versus sell). Throughout the paper, I use the terms market makers and intermediaries interchangeably. The analysis focuses on the period 2011–2023, during which the data explicitly identify market-maker trades. Before 2011, market makers are not separately classified and must be inferred as the counterparty to firms and customers; restricting attention to the post-2011 sample also benefits from markedly higher option liquidity, yielding more reliable estimates of intermediaries' trading patterns at high frequency.

S&P 500 index options have a contract multiplier of 100, that is, one contract represents 100 units of the underlying index. To facilitate interpretation, I therefore express all option volumes and positions in underlying-equivalent units by multiplying by 100.

Examining market-maker trading activity, I find that intermediaries buy an average of 29.1 million S&P 500 put options per day and sell roughly 30.3 million, implying net purchases of −1.2 million puts daily. Net buys are defined as:

$$\text{Net Buys}_t^i = \text{Buys}_t^i - \text{Sells}_t^i, \tag{3}$$

where i indexes the option contract and t the trading day. In contrast, buy and sell volumes in call options are nearly identical at about 17.5 million contracts per day, resulting in net purchases close to zero.

These patterns reveal that the intermediary sector persistently supplies put options to end-users while maintaining balanced positions in calls, foreshadowing the short-put exposure documented below.

I construct intermediaries' cumulative option positions by aggregating their daily net purchases over the life of each contract:

$$\text{Net Position}_t^i = \begin{cases} \sum_{k=1}^{t} \text{Net Buys}_k^i & \text{if } t \leq \text{Expiry} \\ 0 & \text{if } t > \text{Expiry} \end{cases} \tag{4}$$

Here, k indexes trading days from the start of the sample through day t. Thus, NetPosition_t^i measures the number of contracts of option i that intermediaries are long minus the number they are short at the end of day t. Because options are continuously listed and expire on a rolling basis, this cumulation produces a well-defined time series of intermediaries' outstanding inventory after a short burn-in period. The frequent expirations of derivative contracts are a major advantage when studying intermediary inventory risk. In contrast to equities, where precise measurement of the initial position is crucial and often unobservable, options naturally reset at expiry, eliminating concerns about initial conditions or position drift. I adopt a six-month burn-in period, resulting in a main sample that spans July 2011 to August 2023. Positions are reset to zero at contract expiry.

Table III reports intermediaries' average net positions in S&P 500 options across portfolios sorted by moneyness and time to expiry. Options are assigned to portfolios at the daily market close and reclassified at the next close. The intermediary sector holds an aggregate short position of approximately –17.9 million put contracts, concentrated in short-maturity, deep out-of-the-money puts, where the net position reaches –13.5 million. Negative values indicate that intermediaries are, on average, net short in the respective option category. In contrast, market makers' net positions in call options are slightly positive and display no consistent pattern across portfolios. This asymmetry is consistent with persistent end-user demand for deep out-of-the-money puts as crash protection, leaving intermediaries as the residual sellers of such options. The next subsection examines how this short put exposure translates into equity market risk for intermediaries.

Table III: Intermediaries' Net Position in S&P 500 Options

Puts		Days to Expiry 2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	-13.54	-3.32	-16.86
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	-0.47	-1.47	-1.94
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	0.38	-0.07	0.32
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	0.47	0.17	0.63
All		-13.15	-4.70	-17.85
Calls				
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	-0.84	-0.50	-1.33
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	1.55	0.87	2.42
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	1.40	0.47	1.87
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	0.61	-0.01	0.59
All		2.72	0.83	3.55

Note: This table reports the average net positions of S&P 500 option market makers, sorted by moneyness and days to expiry. The net position equals the number of contracts that intermediaries are long minus the number they are short, aggregated across all trading days. Negative values indicate that intermediaries are, on average, net short in the respective option category. Positions are expressed in millions of contracts and converted to underlying-equivalent units using the 100-share contract multiplier. The sample period spans 2011–2023.

Who buys puts? The literature attributes intermediaries' persistent short positions in S&P 500 put options largely to the hedging demands of sophisticated investors. Lemmon and Ni (2014) link index option trading to institutional hedging motives, noting that trading in single-stock options is more often driven by retail investors. Bollen and Whaley (2004) show that institutional investors hold long positions in index puts as portfolio insurance, and Chen, Joslin, and Ni (2019) interpret customer demand for puts as evidence of investors' aversion to economic crash risk. Similarly, Goyenko and Zhang (2019) document net buying pressure in S&P 500 put options but net selling pressure in calls. Taken together, this evidence indicates that institutional investors are the primary buyers of index puts, motivated by hedging or insurance considerations, and that there is no natural counterparty to supply these contracts. Intermediaries therefore fill this role, resulting in a persistent short position in out-of-the-money puts.

III.B. Intermediaries' Equity Market Risk

The short-put exposure documented above implies that intermediaries are exposed to large declines in the underlying equity index. This subsection quantifies that exposure and illustrates the mechanics through which limited overnight equity liquidity transforms intermediaries' option positions into equity market risk. When the underlying price falls sharply, delta-hedged positions must be rebalanced through substantial equity sales; when trading is illiquid, such adjustments are infeasible, leaving dealers exposed to losses.

To illustrate the mechanism, consider a simple numerical example highlighting the importance of delta-hedging for option risk management. Delta-hedging is of first-order importance for maintaining a neutral exposure, yet it requires trading large amounts of the underlying equity relative to even small option positions. Suppose an intermediary holds a short position in a put option with 7 days to expiry when expected equity return volatility is 30%. At a stock price of 5,200, the option's price is about \$20 with a delta of 0.2. If the stock price declines continuously to 4,800, the option's price increases to roughly \$219 and its delta rises to 0.9. Without hedging, the short put position experiences a return of -995%. An initial delta-hedge would reduce the magnitude of the return to -658% but would require shorting \$884 worth of stock. Achieving a risk-free payoff would require continuously adjusting the hedge as delta changes, implying cumulative equity sales of about \$3,484 per option. This illustrative example underscores why even small short-put exposures can translate into substantial equity market risk for intermediaries. In the next step, I quantify this risk using intermediaries' actual option positions to estimate their aggregate profit-and-loss under different hypothetical equity return scenarios.

I quantify intermediaries' exposure to equity market risk by estimating the profit and loss (PnL) of their aggregate option portfolio under hypothetical equity return scenarios. Specifically, I compute the Scenario PnL as:

$$\begin{aligned}\text{Scenario PnL}_{t+1} = \sum_{i=1}^{I} \text{Net Position}_t^i \times \\ \left[\text{Scenario P}_{t+1}^i - P_t^i \;-\; \Delta_t^i \;\times\; (\text{Scenario SP500}_{t+1} - \text{SP500}_t)\right], \qquad (5)\end{aligned}$$

where Scenario PnL_{t+1} is the estimated PnL over period $t{+}1$; Net Position_t^i denotes intermediaries' net position in option i at the end of day t; Scenario P_{t+1}^i is the estimated option price under the simulated market scenario, Δ_t^i is the option's delta, and Scenario SP500_{t+1} is the assumed value of the S&P 500.

This framework estimates the losses the intermediary sector would incur under different joint realizations of option prices and underlying index levels. The method is flexible and can accommodate various dynamics for both P and $SP500$. To map future option prices to underlying values, I adopt the Black–Scholes–Merton model for simplicity. The choice of pricing model is immaterial for the analysis, as long as option values remain convex in the underlying price, such that large underlying moves induce nonlinear changes in delta. I assume that intermediaries are initially fully delta-hedged but subsequently hold their positions without adjustment, capturing their risk exposure over nights and weekends when equity market liquidity is low.

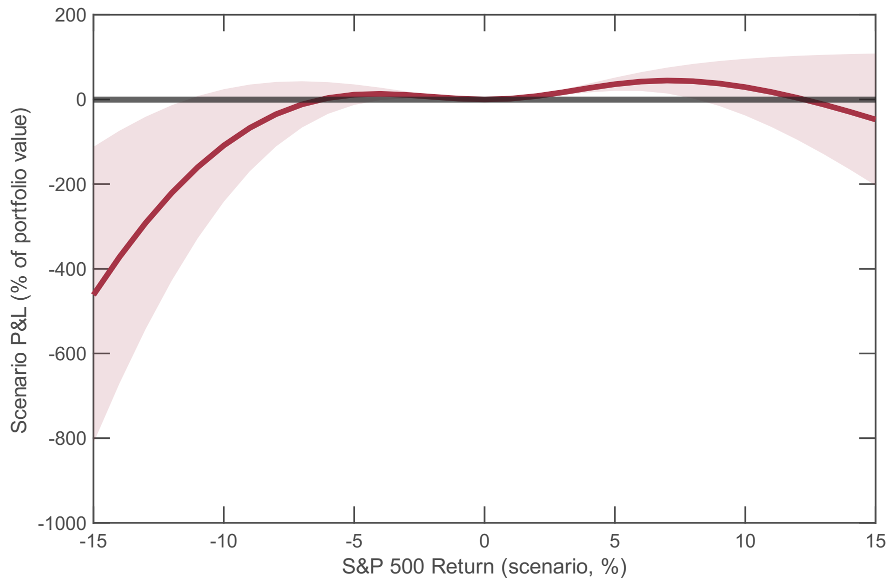
To evaluate Scenario PnL_{t+1} in equation 5 for a hypothetical -10% return in the underlying S&P 500, I compute Scenario P^i_{t+1} as the Black-Scholes-Merton price of option i at the end of period $t+1$, assuming that $\sigma^i_{t+1} = \sigma^i_t$ and Scenario $\mathrm{SP500}_{t+1} = \mathrm{SP500}_t \times 0.9$, where σ describes options' implied volatility relative to the Black-Scholes-Merton model. That is, I change the equity price, under the Black-Scholes-Merton pricing framework, while holding implied volatilities constant. In practice, equity returns and volatility are negatively correlated, and increases in volatility raise option prices. Consequently, the losses reported here likely understate intermediaries' true downside exposure, as incorporating volatility spikes would make losses during market crashes even more pronounced.

Figure 3 shows intermediaries' exposure to equity market risk. The figure shows the intermediary scenario PnL for different hypothetical S&P 500 returns, in % of intermediaries option portfolio value. The figure shows that a -10% return in the S&P 500 index would lead to a portfolio return of about -200%. The losses accrue from price increases on short positions and are thus not capped at -100%. In contrast, small equity price changes lead to moderately positive returns. The estimation does not account for the empirically large option risk premium, and thus does not display the intermediary profits that materialize when absolute equity returns are small.

III.C. Intermediaries' Liquidity Demand for Delta-Hedge Adjustments

Periods of limited equity liquidity expose intermediaries to equity market risk because they constrain their ability to maintain delta-neutral portfolios. This subsection quantifies the volume of equity trading required for intermediaries to remain delta-hedged when the underlying index experiences large price movements. By estimating the liquidity demand implied by intermediaries' option inventory under different equity return scenarios, I show that the scale of these required hedge adjustments far exceeds actual overnight trading volumes for most hours of the night,

Figure 3: Market Makers' Equity Market Risk



Note: The figure shows estimated profits of market makers' option inventory for different hypothetical returns of the underlying S&P 500 equity index. Profits are in percent of the value of market makers' option inventory. Option returns are delta-hedged, but hedges are not adjusted. The shaded area shows the 95% confidence interval. The sample period is 2011 to 2023.

highlighting the practical limits of continuous hedging.

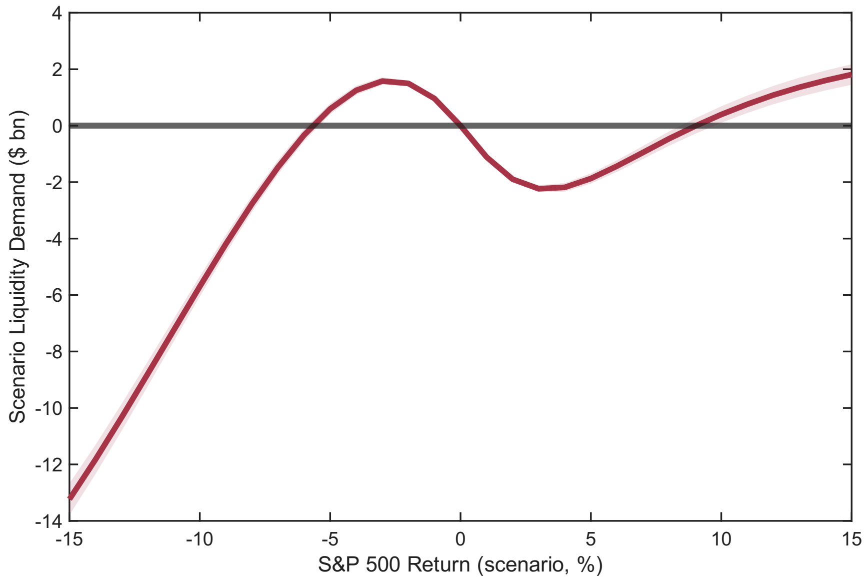
I estimate intermediaries' liquidity demand as:

$$\text{Scenario Liquidity Demand}_{t+1} = \sum_{i=1}^{I} NetPosition_t^i \times \left[Scenario\Delta_{t+1}^i - \Delta_t^i\right] \times SP500_t, \quad (6)$$

where Scenario Liquidity Demand$_{t+1}$ denotes the estimated dollar trading volume required for intermediaries to maintain delta-neutral positions following a hypothetical change in the underlying. $NetPosition_t^i$ is intermediaries' net position in option i at the end of day t as defined earlier. Δ_t^i is options' Black-Scholes-Merton delta, calculated using the option's implied volatility σ_t^i. $Scenario\Delta_{t+1}^i$ is the estimated delta under the simulated market scenario, where where $\sigma_{t+1}^i = \sigma_t^i$ and $SP500_{t+1} = SP500_t \times \mu$. The parameter μ takes values of $[0.85, 0.9, ..., 1.15]$ to simulate S&P 500 returns of $[-15\%, -10\%, ..., 15\%]$.

Intermediaries' liquidity demand for maintaining delta-hedges amounts to several billions of dollars. Figure 4 plots the estimated liquidity demand from Equation 6 across hypothetical S&P 500 return scenarios. If the underlying index declines by 10%, intermediaries would need

Figure 4: Liquidity Demand for Delta-Hedge Adjustments



Note: This figure plots intermediaries' estimated liquidity demand required to maintain delta-hedged positions under hypothetical S&P 500 return scenarios, as defined in Equation 6. Liquidity demand is measured in billion dollars and represents the trading volume needed to offset changes in portfolio delta. The shaded area shows the 95% confidence interval. The sample period is 2011–2023.

to sell approximately $8 billion worth of equities to remain delta-hedged. This required trading volume far exceeds typical overnight activity in equities and futures between 20:00 and 04:00, when markets are thinly traded. Consequently, intermediaries face severe constraints on hedge adjustments during these periods, exposing them to substantial inventory risk.

These estimates likely represent a lower bound. Investors' strong demand for crash protection implies that intermediaries hold short positions in options beyond the S&P 500 contracts examined here. Moreover, option deltas rise with expected volatility, which typically spikes during large negative equity market moves, further amplifying intermediaries' liquidity needs precisely when market depth is at its lowest.

III.D. Intermediaries' Shadow Gamma

Intermediaries' inventory risk is driven by options' shadow gamma—the state-contingent curvature that emerges after large underlying moves—rather than by contemporaneous gamma. Gamma captures the local curvature of option values and thus the extent to which delta hedges become imperfect for small price changes. Over 2011–2023, however, intermediaries' aggregate gamma hovers around zero and, if anything, is slightly positive, implying gains from underlying price changes, not losses. This measure misses the core exposure because dealers' dominant position is short deep out-of-the-money puts: these contracts suffer large losses in a crash yet contribute little to current gamma, since deep-OTM gamma is near zero. Evaluated under large price moves, by contrast, intermediaries' inventories load on substantial negative shadow gamma. Positions that are well balanced for small fluctuations become acutely exposed when the underlying moves by a large amount, generating equity-market risk and inventory losses, especially overnight when hedge adjustments are constrained.

I estimate intermediaries' inventory gamma as:

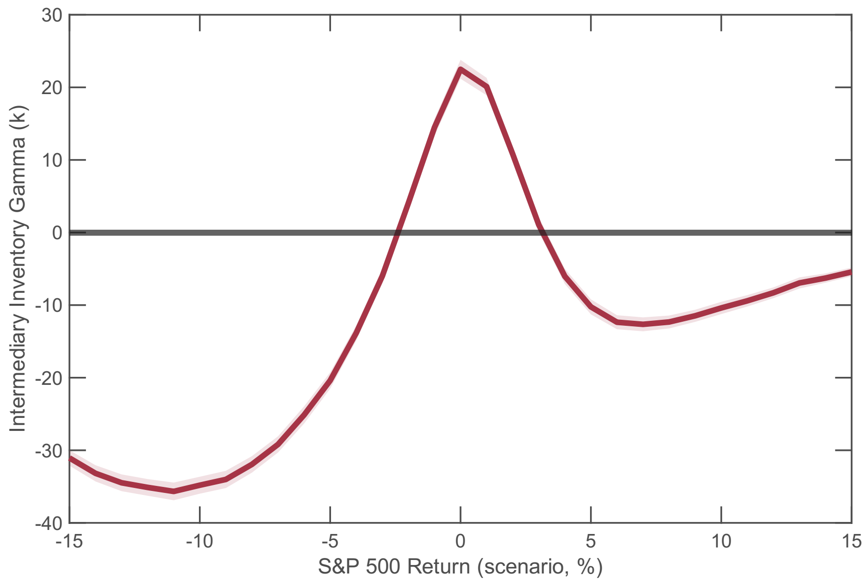
$$\text{Intermediary Gamma}_{t+1} = \sum_{i=1}^{I} \text{Net Position}_t^i \times \text{Option Gamma}_t^i, \tag{7}$$

where $NetPosition_t^i$ denotes intermediaries' net holdings of option i at time t, and $OptionGamma_t^i$ is the option's gamma evaluated under a hypothetical equity-market return. I compute shadow gamma across a grid of counterfactual S&P 500 returns from -15% to $+15\%$, which captures the curvature of intermediaries' portfolio value under large price moves rather than infinitesimal changes. This construction links measured portfolio risk directly to the nonlinear exposure dealers face when equity liquidity constraints impede continuous re-hedging.

Figure 5 plots intermediaries' inventory gamma across hypothetical S&P 500 returns. The gamma at a return of zero corresponds to intermediaries' current exposure and is slightly positive, implying that small equity moves generate gains rather than losses. This measure therefore fails to capture intermediaries' inventory risk over nights and weekends, when large price changes are most relevant. For both positive and negative equity moves, the estimated shadow gamma turns negative, reflecting the expected losses on intermediaries' short positions in deep out-of-the-money puts following a market decline. Figure A.3 contains a binscatter of intermediary market risk against intermediary shadow gamma and shows a strong positive relation between the two.

At-the-money gamma remains positive, indicating that dealers profit from small price fluctuations while bearing risk from large ones. This pattern is consistent with Hu, Kirilova, and Muravyev (2023), who find limited delta-hedging by option intermediaries in Korean markets. My results suggest that intermediaries' portfolios are locally well balanced against small underlying

Figure 5: Intermediary Gamma Across Hypothetical S&P 500 Returns



Note: This figure plots intermediaries' aggregate inventory gamma for the actual and several hypothetical values of the S&P 500 index. Inventory gamma is computed as the sum product of intermediaries' net positions across option contracts and the respective options' gamma, defined as the second derivative of the option value with respect to the underlying price. Negative gamma indicates expected inventory losses under large equity moves. The shaded area shows the 95% confidence interval. The sample period is 2011–2023.

moves but become increasingly exposed as price changes grow in magnitude.

My approach to measuring intermediaries' exposure to equity market risk differs fundamentally from existing work. Since Garleanu, Pedersen, and Poteshman (2009), the literature has typically estimated intermediary risk using net gamma and net vega, which proxy for exposure to jump and volatility risk, respectively. Net gamma, the sum product of intermediaries' net option positions and each contract's gamma, captures how much dealers' delta-hedges must adjust in response to small price movements of the underlying. Gamma, the second derivative of the option value with respect to the underlying price, thus measures the local curvature of intermediaries' portfolio value around current market conditions. This local measure is informative when jumps are small and trading is continuous, since in such settings the underlying rarely departs far from its current level.

However, this framework cannot account for the pronounced premia in out-of-the-money puts relative to calls. Because puts and calls with identical contract specifications share the same gamma, net-gamma–based measures would imply symmetric risk premia, contrary to the data. Moreover, gamma is highest for at-the-money options, whereas observed risk premia are largest for short-maturity, deep out-of-the-money puts. If conventional gamma captured intermediaries' primary exposure, the most expensive contracts should be at-the-money, which the evidence rejects.

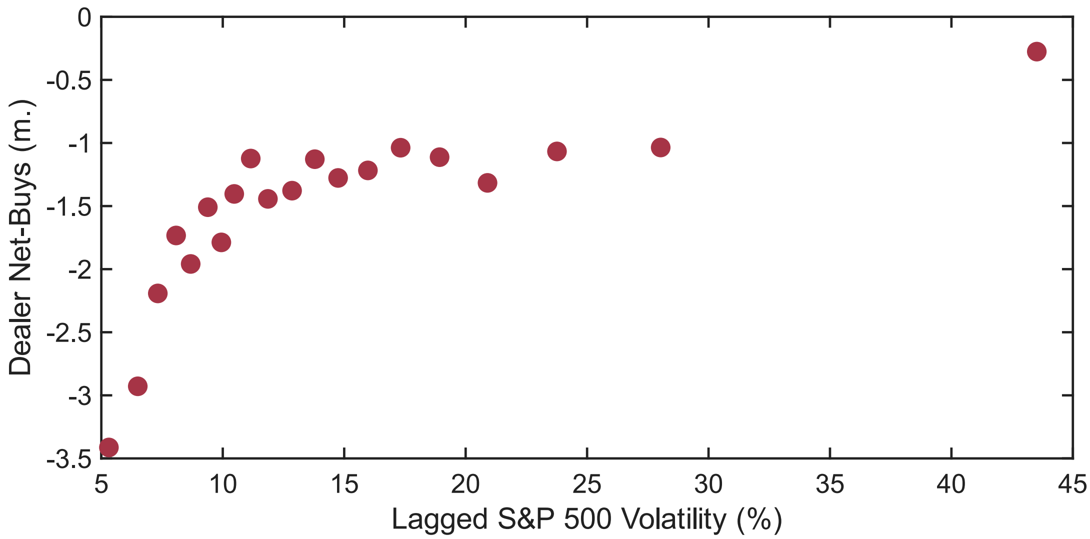
In contrast, I show that intermediaries' risk arises from exposure to large, infrequent price movements, rather than small price fluctuations. This risk emerges from the daily market close of equity exchanges and the resulting overnight illiquidity, which prevents continuous delta-hedging. Consequently, out-of-the-money puts are especially risky for intermediaries, and their elevated risk premia reflect compensation for this shadow-gamma exposure.

III.E. Intermediaries' Inventory Adjustment and Risk Management

Intermediaries adjust their option inventories systematically in response to changing market conditions. They sell more put options when equity market volatility is low, indicating that (*i*) they actively manage exposures rather than passively absorb investor demand, and (*ii*) equity market risk is a central component of their overall inventory risk. Gruenthaler (2022) documents that option intermediaries manage their net-vega positions in anticipation of spikes in implied volatility. I provide complementary evidence that intermediaries manage their exposure to equity market risk. This behavior reinforces the interpretation that option risk premia arise primarily overnight, when limited equity liquidity constrains delta-hedging and leaves intermediaries exposed to unhedgeable inventory risk.

Intermediaries' trading behavior provides evidence of active risk management in response to changing equity market conditions. Figure 6 plots intermediaries' daily net purchases of S&P 500 puts against lagged realized equity volatility. The relationship is strongly negative: when volatility is low at around 5% intermediaries sell roughly 3.4 million puts per day; when volatility is high at around 17% daily sales decline to about 1 million contracts. The pattern is nearly monotonic and appears concave, suggesting diminishing sensitivity at higher volatility levels. Although the figure does not separately identify shifts in customer demand, it is more plausible that dealers scale back put sales when volatility rises than that customers reduce demand when markets are calm. This trading pattern supports the interpretation that intermediaries manage their short-put exposure countercyclically, increasing risk-taking when equity market risk is low and retrenching when risk is high. This behavior is consistent with inventory management motives rather than passive order flow accommodation.

Figure 6: Intermediary Put Trading By Lagged Equity Return Volatility



Note: This figure plots intermediaries' net purchases of S&P 500 put options against lagged equity market volatility. Net purchases are measured as daily buys minus sells (in millions of contracts). Volatility is computed as the standard deviation of close-to-close S&P 500 returns over a rolling 10-day window, lagged by one day. The downward slope indicates that intermediaries sell more puts when recent volatility is low, consistent with active inventory risk management. The sample period is 2011–2023.

IV. The Option Risk Premium and Intermediary Inventory Risk

This section documents that option risk premia are concentrated almost entirely overnight. Delta-hedged option returns are strongly negative between the market close and the next morning's open, but indistinguishable from the risk-free rate during regular trading hours. This timing pattern supports the interpretation that negative option returns compensate intermediaries for bearing inventory risk when equity markets are illiquid. Consistent with this mechanism, I show that intermediaries' shadow gamma—the measure of exposure to large, unhedgeable equity price moves—significantly predicts overnight option returns, particularly for contracts with high shadow gamma.

IV.A. The Option Risk Premium Materializes at Night

Data: High-Frequency Option Returns. I use high-frequency data on S&P 500 index options from the Chicago Board Options Exchange (CBOE). The dataset aggregates observations at 15-minute intervals, beginning at 09:45 E.T. (fifteen minutes after the regular market open) and ending at 16:15, the official market close. For each interval, it reports bid and ask quotes, as well as first, last, high, and low trade prices. The data further include option volume, open interest, and pre-computed risk measures such as delta and gamma. A detailed description of U.S. high-frequency option data and its construction is provided in Andersen, Archakov, Grund, Hautsch, Li, Nasekin, Nolte, Pham, Taylor, and Todorov (2021).

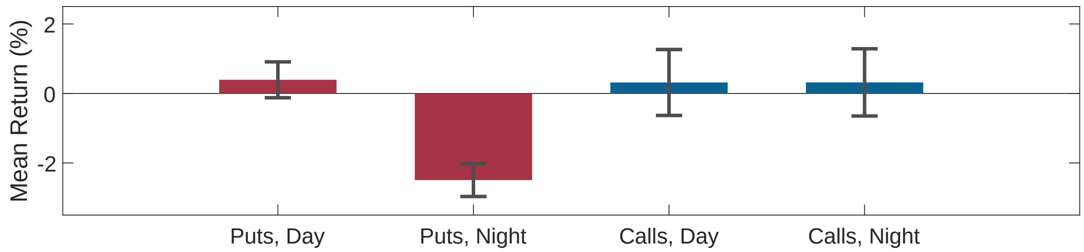
To mitigate concerns about liquidity and data quality, I apply a series of standard filters. I exclude options with zero trading volume on any of the previous three days or with zero volume at the start of the return period. Accordingly, to be included in the night (day) portfolio, an option must have traded for three consecutive days and have a valid trade between 16:00–16:15 (09:30–09:45) prior to the return interval. I remove observations with negative lagged bid–ask spreads, zero bids, or lagged mid-quotes below \$0.05. I also exclude extreme reversal returns, exceeding 1,000% in one period and –90% in the next. Finally, I discard all violations of no-arbitrage bounds. Merging the resulting dataset with intermediary position data yields the main sample period of 2011–2023. All filters are based solely on lagged information and thus avoid look-ahead bias. These procedures closely follow Jones and Shemesh (2018) and Muravyev and Ni (2020).

I measure night returns from 16:15 to 09:45 (E.T.) and day returns from 09:45 to 16:15. Open prices are recorded at 09:45 because the dataset aggregates quotes into 15-minute intervals; this timing also mitigates concerns about illiquid opening quotes. Throughout the analysis, I use mid-quotes to measure prices. Option returns are delta-hedged with S&P 500 E-Mini futures at the start of each period: the night-time hedge is established at 16:15 and held constant until the next morning. Option deltas are estimated from the Black–Scholes–Merton model, setting the volatility of the underlying equal to the option's lagged implied volatility. Implied volatility is lagged to avoid bias from the negative correlation between volatility and market returns. All results are robust to alternative delta specifications. Option returns are reported in excess of the risk-free rate, which is negligible over intraday or overnight horizons and thus does not affect the results.

Figure 7 shows summary statistics for delta-hedged option returns. The two left bars contain out-of-the-money put options, the two right bars show out-of-the-money calls. Over my sample S&P 500 put option experienced an average night return of -2.49%.[6] The associated Newey-West t-statistic exceeds 10. In contrast, put option intraday returns average only 0.39%. The difference

[6] Average returns are not annualized. Option risk premia are very large relative to most other traded assets.

Figure 7: Option Risk Premia During the Day and Overnight



Note: This figure plots average delta-hedged returns of out-of-the-money S&P 500 put and call options over day and night periods. Bars show mean returns with 95% confidence intervals. Day returns are measured between 09:45 and 16:15 (E.T.), and night returns between 16:15 and 09:45. Returns are delta-hedged at the start of each period and expressed in percent. The sample period is 2011–2023.

between night and day returns is highly significant. In contrast, S&P 500 call options experienced an average night return of 0.32% and an equal average day return. Neither the night return, the day return or the difference between the two is significantly different from zero for call options. Thus, negative option risk premia are concentrated in puts and arise almost entirely overnight.

The strong concentration of option risk premia overnight suggests that returns are linked to periods when intermediaries face the greatest difficulty adjusting their hedges. To test this mechanism directly, I next relate overnight option returns to measures of option level risk and intermediary inventory risk.

IV.B. Option Returns and Shadow Gamma

To test whether shadow gamma and intermediary inventory explain option returns, I estimate the following specification:

$$
\begin{aligned}
R_t^i = \beta_0 \mathbf{1} + \beta_1 \text{Option Gamma}_{t-1}^i + \beta_2 \times \text{Intermediary Gamma}_t \\
+\beta_3 \text{Option Gamma}_{t-1}^i \times \text{Intermediary Gamma}_t + \epsilon_t^i,
\end{aligned}
\tag{8}
$$

where $R_{i,t}$ denotes the overnight, delta-hedged return of option i, in basis points. $OptionGamma_{t-1}^i$ is the lagged shadow gamma of option i, evaluated for hypothetical S&P500 returns of (-15%, -10%, -5%). $IntermediaryGamma$ measures intermediaries inventory gamma. Explanatory variables are standardized to zero mean and unit variance. Standard errors are double-clustered by

Table IV: Option Returns and Intermediary Shadow Gamma

	(1) −15%	(2) −10%	(3) −5%
Shadow Gamma	-150.1***	-159.8***	-82.8***
	(-7.46)	(-7.11)	(-3.67)
Intermediary Shadow Gamma	23.2	14.8	20.0
	(0.73)	(0.53)	(0.80)
Shadow Gamma	40.9***	24.4*	26.2**
× Intermediary Shadow Gamma	(2.81)	(1.90)	(2.00)
Constant	-217.5***	-216.2***	-214.3***
	(-6.06)	(-6.02)	(-5.97)
Observations	954,386	954,386	954,386
R2-adjusted	0.00	0.00	0.00

Note: This table reports estimates of Equation 8, which regresses overnight, delta-hedged option returns on lagged option-level shadow gamma and intermediaries' aggregate shadow gamma. Columns (1)–(3) use shadow gamma evaluated under hypothetical S&P 500 returns of −15%, −10%, and −5%, respectively. Option returns are measured in basis points and standardized explanatory variables have zero mean and unit variance. Standard errors are double-clustered by trading day and option identifier. The sample period is 2011 to 2023.

trading day and option identifier.

Table IV shows that average overnight delta-hedged option returns are strongly negative (about −214 to −218 bps), consistent with the concentration of premia outside regular trading hours. A one standard deviation increase in option level shadow gamma predicts substantially more negative overnight returns: −150.1 bps (−15% scenario), −159.8 bps (−10%), and −82.8 bps (−5%), all highly significant. The effect strengthens as the hypothetical move becomes larger (from −5% to −10%), and remains large at −15%. These loadings line up with the cross-section: contracts with the highest shadow gamma are short-dated, deep OTM puts (see Table A.5), which also earn the most negative overnight returns (see Table A.6).

The aggregate intermediary shadow gamma term is small and statistically indistinguishable from zero on its own, but the interaction between option-level and intermediary shadow gamma is negative and significant in two of three specifications (and marginal in the third). This implies that the return penalty associated with option-level shadow gamma is larger in states when dealers' aggregate exposure is elevated in absolute terms, consistent with the paper's mechanism linking contract-level curvature risk to intermediaries' inventory risk when hedging is constrained overnight. The insignificant coefficient on Intermediary Shadow Gamma is consistent with intermediary risk management: Higher intermediary shadow gamma leads to higher option returns, but intermediaries take less risk in risky times, thus muting this relation. Overall, the estimates support the main message: shadow-gamma exposure explains both the timing (overnight) and the cross-section (deep OTM puts) of option risk premia.

V. Conclusion

This paper shows that the option risk premium arises from intermediaries' inventory risk, which stems from overnight equity illiquidity. Option returns are strongly negative overnight, precisely when delta-hedge adjustments are most constrained, but indistinguishable from zero during trading hours, when equities are highly liquid. Exploiting the expansion of overnight equity trading around 2006, I document that improved equity liquidity significantly reduced the magnitude of the option risk premium, particularly for short-maturity out-of-the-money puts where dealers' short exposures are concentrated. A new measure, shadow gamma, captures intermediaries' sensitivity to large, unhedgeable price moves and explains both the timing and cross-section of option returns.

The results have two broader implications. First, from a market-design perspective, the evidence suggests that increasing around-the-clock equity trading can lower hedging costs and compress derivative risk premia by improving intermediaries' ability to manage inventory risk. Second, from an asset-pricing perspective, the findings highlight that liquidity frictions and intermediary constraints jointly determine the price of risk. Derivative markets therefore provide a clean setting in which to observe how institutional frictions give rise to persistent and economically large risk premia.

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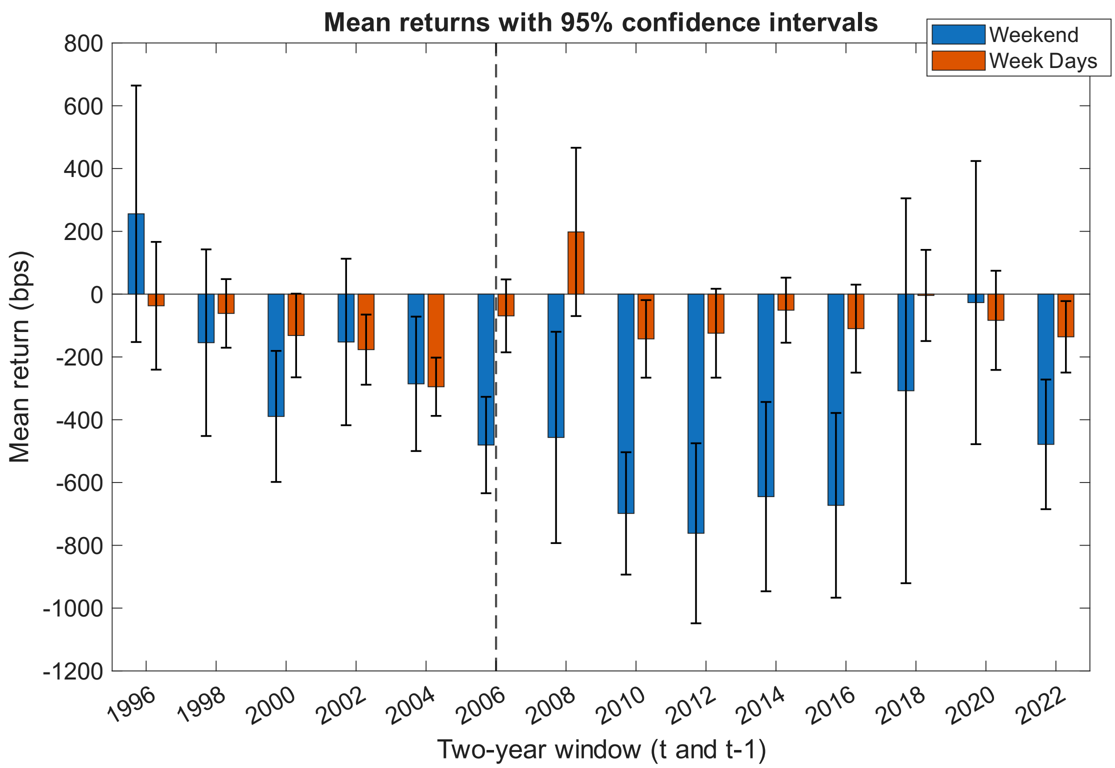
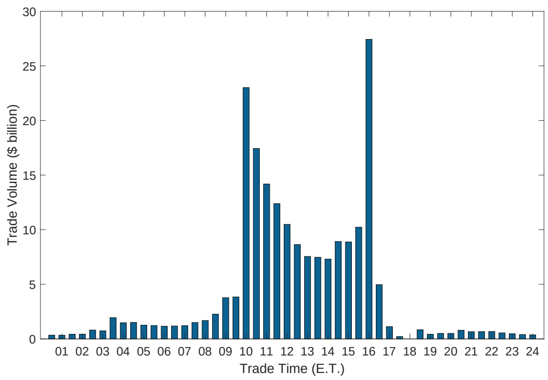
A.1. Appendix Figures

Figure A.1: Mean Option Returns by 2-year Period

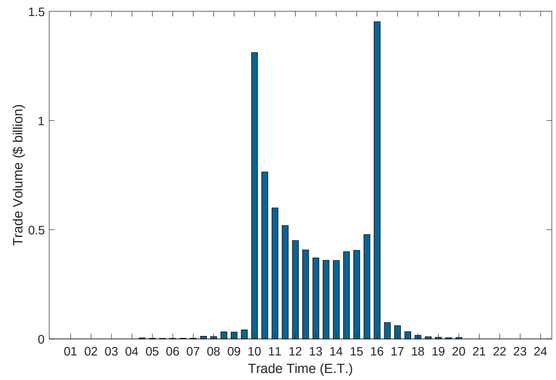


Note: This figure shows average week-night and weekend option returns over 2 year periods. The left bars show mean returns over weekends. The right bars show mean returns over week days. The error bars show the 95% confidence interval. The vertical line indicates the emergence of overnight equity trading around 2006.01. Returns are for the portfolio of out-of-the-money puts, are delta-hedged and are in basis points.

Figure A.2: Equity Trade Volume Around the Clock



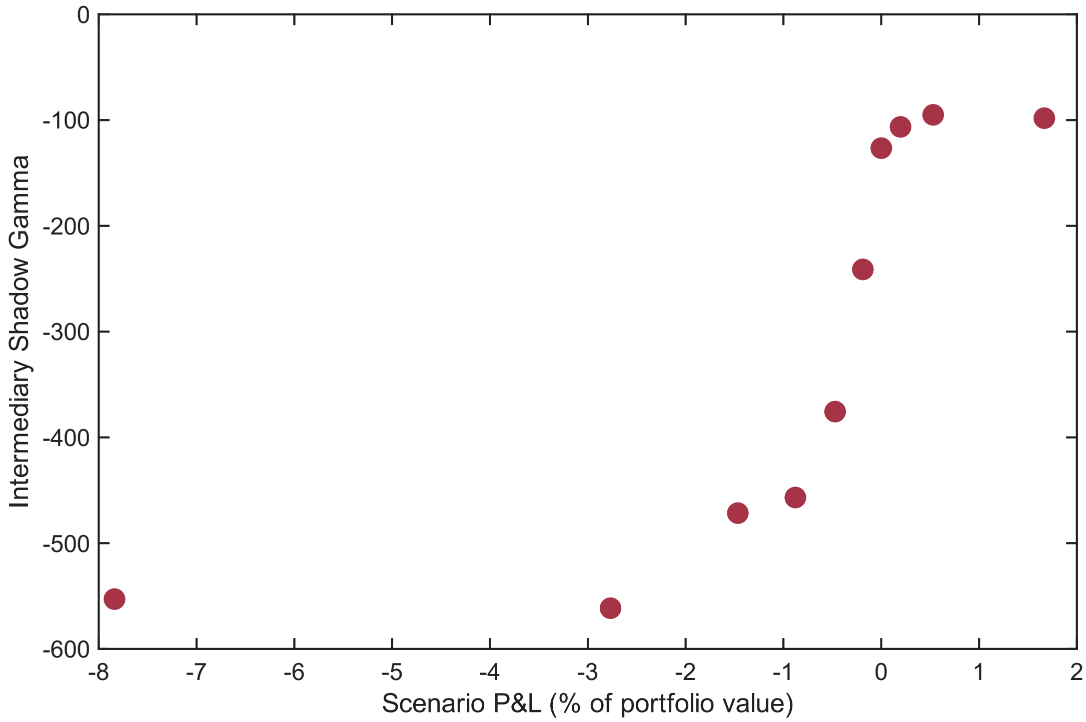
(a) Futures



(b) Apple Inc.

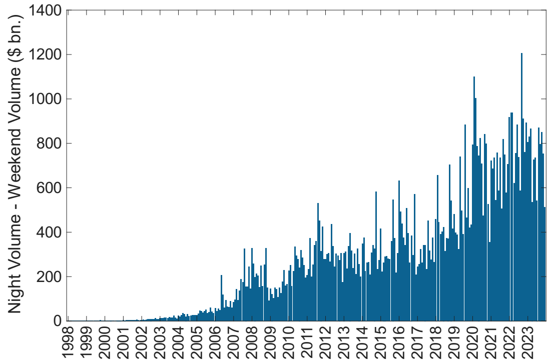
Note: The figure shows average trade volumes for each 30-minute interval of the day. Panel (a) contains the most liquid S&P 500 E-mini futures contract, panel (b) contains Apple Inc. stocks, to provide an idea of overnight trade volumes in stocks themselves. The sample period is 2011 to 2023.

Figure A.3: Market Makers' Equity Market Risk and Inventory Shadow Gamma

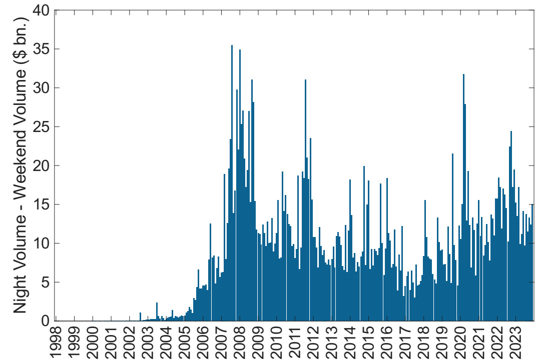


Note: This figure shows market makers inventory shadow gamma by level of market maker scenario P&L. Shadow gamma and scenario P&L are measured at -15%. The scenario P&L is truncated at percentiles 2.5 and 97.5. The sample period is 2011 to 2023.

Figure A.4: The Emergence of Overnight Equity Trading Relative To Weekends



(a) S&P 500 Futures



(b) S&P 500 ETF

Note: This figure shows the rise of overnight equity trading activity in S&P 500 instruments over week-nights, relative to weekends. Panel (a) reports the monthly sum dollar volume transacted overnight in the most actively traded S&P 500 E-mini futures contract over weeknights minus weekends. Weekends are measured from Friday 18:00 to Monday 09:30. Week-nights are all other nights. Panel (b) shows the corresponding series for the SPY ETF. Weekends trading is defined as transactions between Friday 16:00 and Monday 09:30 (E.T.). Week-nights are all other nights. Volumes are expressed in billions of dollars.

A.2. Appendix Tables

Table A.1: The Impact of Stock Trading on Option Spreads: Diff-in-Diff

	Absolute Spread (cents)			Relative Spread (bps)		
	(1) Baseline	(2) Winsorized	(3) Excl. Crashes	(4) Baseline	(5) Winsorized	(6) Excl. Crashes
Intra-week	4.3***	3.7***	4.3***	1.6***	1.6***	1.6***
	(3.75)	(3.67)	(3.75)	(3.12)	(4.47)	(3.12)
Post	14.9***	8.8**	10.6**	-26.2***	-23.8***	-26.4***
	(2.88)	(2.28)	(2.37)	(-14.69)	(-20.54)	(-14.91)
Intra-week x Post	-7.1***	-5.8***	-6.5***	-1.4**	-1.2***	-1.2**
	(-3.87)	(-4.32)	(-3.93)	(-2.39)	(-3.12)	(-2.25)
Constant	97.6***	97.4***	97.6***	38.7***	36.0***	38.7***
	(34.43)	(36.95)	(34.43)	(23.42)	(37.11)	(23.42)
Observations	6,958	6,958	6,812	6,955	6,955	6,809
R2-adjusted	0.01	0.00	0.00	0.44	0.52	0.44

Note: This table reports estimates from a difference in differences specification that includes indicators for treated periods (IntraWeek), and the post-event period. Intra-week spreads are daily option spreads at close, except Friday. *Post* indicates the period after 2006.01 when overnight stock trading emerged. Spreads are measured for the portfolio of out-of-the-money S&P 500 puts. Columns 1 to 3 show absolute spreads in cents, columns 4 to 6 show relative spreads in basis points. Columns (2) and (5) winsorize option spreads at percentiles 5 and 95. Columns (3) and (6) exclude the crash months of 2018.02 and 2020.02 to 2020.04. Standard errors are clustered within every month. The sample period is 1996 to 2023.

Table A.2: Overnight Equity Liquidity and Option Returns: Continuous-Treatment Estimates

	(1)	(2)	(3)
Liquidity x OTM puts	293.3***	153.5***	347.4***
	(4.77)	(5.18)	(5.72)
Day	Yes	Yes	Yes
ID x Month	Yes	Yes	Yes
Observations	51,696	51,696	50,529
R2-adjusted	0.36	0.29	0.34

Notes: This table reports panel regressions of portfolio-level, delta-hedged option returns (basis points) on a continuous equity-liquidity measure and its interaction with an indicator for deep out-of-the-money (OTM) puts. Liquidity is the trading volume of the front-month E-mini S&P 500 futures contract measured over the night period of the corresponding return window, scaled by the number of hours in that night window and standardized to zero mean and unit variance. The specification includes fixed effects for the return-window date and for option-portfolio $\times$ month; main effects of liquidity and the OTM-put indicator are therefore absorbed. Returns are computed for eight OTM portfolios (four puts and four calls) with breakpoints defined in Table A.6, using all daily close-to-close observations. Column (1) reports the baseline estimates; column (2) winsorizes returns at the 5th and 95th percentiles; column (3) excludes February 2018 and February–April 2020. Standard errors are two-way clustered by option portfolio and return-window date. Sample period: 1996–2023.

Table A.3: The Impact of Stock Trading on VIX Futures Returns: Diff-in-Diff

	Intra-week	Post	Intra-week $\times$ Post
Coefficients	65.4	-63.4	51.2
t-stats	3.4	-2.9	1.5

Note: This table reports estimates from regressing daily VIX futures returns on an indicator for intra-week returns and an indicator for the period post 2006.01, when overnight equity trading emerges. Returns are daily close-to-close, so the intra-week indicator marks returns between Monday close and Friday close. Returns are measured from VIX futures mid quotes and are in basis points. $t-$ statistics are Newey-West with 10 lags. The sample period is 2004.04 to 2007.12.

Table A.4: S&P 500 Equity Returns

	Mean	Std	Min	P1	P50	P99	Max
Day	1.40	78.60	-522.09	-244.11	4.61	203.85	446.21
Night	2.95	69.77	-712.16	-206.77	5.90	174.04	570.02

Note: This table displays summary statistics for S&P 500 equity returns. Returns are measured via S&P 500 E-Mini futures and are in basis points. Day returns are from 09:30 to 16:15 (E.T.), night returns are from 16:15 to 09:30, and both are calculated from trade prices. P1 indicates the first percentile. The sample period is 2011 to 2023.

Table A.5: Options' Shadow Gamma, at -10%

Puts		Days to Expiry 2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	1,207.6	176.0	1,464.7
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	132.5	109.9	245.0
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	23.0	21.8	45.4
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	2.2	1.6	3.9
All		1,365.4	310.3	1,762.8
Calls				
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	5.4	9.6	15.2
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	28.4	41.6	70.8
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	73.7	52.8	128.0
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	130.8	17.5	155.8
All		252.6	121.6	392.5

Note: The table shows options' shadow gamma. Shadow gamma is the expected option gamma, conditional on a hypothetical return in the underlying asset. This table displays options shadow gamma for an S&P 500 return of -10%. Shadow gamma is multiplied by 1000 for readability. The sample period is 2011 to 2023.

Table A.6: The Cross-Section of Night Returns

Puts		Days to Expiry 2-70	71-	All
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	-390.1	-17.6	-307.1
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	-87.8	-24.3	-71.7
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	-59.7	-21.6	-47.6
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	-69.0	-63.8	-63.4
All		-297.8	-22.2	-233.3
Calls				
$0.00 \leq \lvert\Delta\rvert \leq 0.25$	Deep Out of the Money	71.3	34.8	65.5
$0.25 < \lvert\Delta\rvert \leq 0.50$	Out of the Money	-8.0	-19.8	-7.1
$0.50 < \lvert\Delta\rvert \leq 0.75$	In the Money	-24.0	-12.9	-21.9
$0.75 < \lvert\Delta\rvert \leq 1.00$	Deep In the Money	-19.8	-7.7	-16.7
All		21.0	-1.2	14.9

Note: The table shows average S&P 500 put returns for eight portfolios, sorted by days to expiry and moneyness. Returns are measured from option market close at 16:15 to the subsequent market open at 09:45. Returns are in basis points and are delta-hedged at the beginning of the respective period. Newey-West t-statistics are in brackets. The sample period is 2011 to 2023.