Inelastic Hedging Demand and Intraday Momentum

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Abstract

Delta-neutral hedging in options with short gamma exposure can result in nonlinear losses that make the demand for underlying assets inelastic. The inelastic hedging demand exacerbates intraday momentum and price fluctuations. With a large sample of stock options, we demonstrate that inelastic demand arises outside the break-even ranges of hedging short gamma exposure, strengthening intraday momentum for the underlying stock. Using the data on options holdings, we show that intraday momentum is stronger when options market makers (MMs) have short gamma exposure. We also find that the option MMs often maintain delta-neutral hedging instead of unwinding their options positions even when the underlying prices hit the break-even ranges. Overall, this paper provides evidence of how the inelastic demand of financial intermediaries generates excessive price volatility via the mechanism of delta-neutral hedging.

JEL classification: G12, G15, G40
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1 Introduction

Inelastic demand can generate large fluctuations in asset prices (Gabaix and Koijen (2022)). Recent research shows low demand elasticity in the U.S. stock markets, and ongoing research explores the causes of this phenomenon. The known causes include financial frictions and regulations. We posit the question of whether the design of trading mechanisms could cause elastic demand. We start with the findings in Baltussen, Da, Lammers, and Martens (2021) that hedging demand in the options market creates intraday momentum for the underlying asset prices and make the point that hedging in options can result in nonlinear losses that make the demand for underlying stocks inelastic when stock prices have large fluctuations. This mechanism was illustrated in the recent events that have reignited the urgency in understanding how options trading could destabilize underlying stock markets.[1] We aim to examine whether demand inelasticity induced by option hedging demand exists persistently and pervasively in the U.S. stock markets.

The causes of extreme price fluctuations in the GME episode include the traditional short-sale squeeze and the notable surge in gamma hedge demand from delta-neutral traders, such as market makers (MMs) in the options market, leading to a so-called "gamma squeeze."[2] During that time, options trading volume and open interest (OI) recorded highs, and so the delta-neutral trader who held the majority of the counterpart position against the end user faced a larger size of the short OI and, subsequently, a larger size of short gamma exposure. This short gamma position could force them to make trend-following trading on the underlying stock in the same direction as its initial movement.[3]

More importantly, the book losses of the delta-neutral hedging could increase nonlinearly

[1] On January 27, 2021, Gamestop (GME) stock recorded a +1,744% year-to-date increase, which was triggered by crowds of retail investors gathered on social media.

[2] A staff report from SEC (2021) 'Staff Report on Equity and Options Market Structure Conditions in Early 2021' released on October 14, 2021, from the Securities and Exchange Commission attributes this surge, in part, to what is known as a "squeeze," a phenomenon where heightened short-sale interest can trigger a massive buyback when share prices rise.

[3] Section 2.1(a) explains in detail its behavior. Generally speaking, if the underlying market moves up, then MMs carrying short gamma need to buy the underlying asset at an unfavorable higher price to neutralize their delta position changed by their short gamma exposure. Conversely, they need to sell at an unfavorable lower price in response to the underlying asset moving down. Although MM carries long gamma more commonly, as shown in Gârleanu, Pedersen, and Poteshman (2009) and Christoffersen, Goyenko, Jacobs, and Karoui (2017), short gamma position, even with less frequent cases, can have potentially catastrophic consequences, providing a compelling reason to study this topic more deeply.

because of the mechanics in option pricing.[4] Therefore, when having a short gamma exposure, the options market MMs face exponential losses with large upside (downside) movements in the underlying stocks and are forced to buy (sell) more stocks to keep the delta-neutral positions by the end of the day. In other words, their short gamma exposure from option markets combined with large price movements in the underlying assets generates inelastic demand for the underlying assets. Our research question emerges: How does the inelastic demand for delta hedging by option traders impact the returns of the underlying asset?

Unlike the straightforward process of a short squeeze, which originates from a short-sale position, the inelastic trading demand driven by a gamma squeeze operates through a more complex mechanism. This mechanism can potentially repeat multiple times, influenced by the magnitude of movement in the underlying asset, and the required size of trades may also fluctuate over time or due to the moneyness of the options. Understanding their impact on underlying assets is, therefore, crucial for studying excessive volatility. Additionally, over the past decade, the volume of option delta-neutral traders has surged alongside the growth of retail investors[5], highlighting the urgency for further academic study on this topic.

To understand their inelastic hedge behavior and impact, this paper studies the concept of inelastic demand arising from hedge mandates due to book PnL changes stemming from gamma and theta exposure. The key to the identification of MMs' inelastic demand is the nonlinear relationship between their PnL and underlying stock returns. To capture this nonlinear relationship, this paper designs a novel measure, called break-even range. By examining the breakeven points of gamma loss (profit) and theta profit (loss), this study aims to elucidate how inelastic hedge demand from book PnL affects underlying asset demand. When MMs maintain a short gamma imbalance in their book positions, any market movement generates negative gamma PnL, offset by positive theta PnL. Consequently, there are two breakeven points between gamma and theta PnL in both directions on each trading day. Beyond these gamma-theta breakeven ranges (GTBR), net PnL turns negative, compelling MMs to rebalance their delta positions to avoid exponential losses, as shown in Figure 2. This rebalancing creates inelastic demand for the underlying asset. Building upon the methodology of Gao, Han, Li, and Zhou (2018), this paper empirically tests whether these

[4]See Figure 2.

[5]See https://qz.com/1969196/citadel-securities-gets-almost-as-much-trading-volume-as-nasdaq

GTBRs serve as inflection points for nonlinear intraday momentum.

The first main findings from empirical testing indicate that when inelastic hedge demand is created by hitting the GTBR, market intraday momentum surges. In addition, on average, when the ranges are hit, option MMs do not unwind their positions but rather maintain delta hedging positions, contributing to a larger momentum effect. This finding expands the current literature on demand-based asset pricing. While previous research has focused on asset returns via the inelastic demand channel of institutions, this study investigates the impact of asset prices via the inelastic demand channel of option MMs, a financial intermediary. Secondly, it finds that intraday momentum via MMs' gamma imbalance does not exist even when they hold a short gamma position, as long as the underlying stock does not reach these breakeven points. This discovery is significant because earlier work mainly focused on MMs' contribution to intraday momentum merely through gamma imbalance, but this study clarifies how it occurs and provides a clearer picture of their behaviors. Lastly, this paper demonstrates that the inelastic demand for MMs is caused not just by gamma imbalance but also by professional investors' option demand. Compared to the current demand-based asset pricing literature studying passive institutions' inelastic demand, this finding clarifies the asset pricing implications of the inelastic demand of active institutions, which drives option markets and indirectly impacts underlying asset prices through option MMs' gamma hedge.

This work adds to a large body of literature on price processes such as momentum, price discovery using derivatives market data, intermediary asset pricing, and demand-based asset pricing. First, a significant body of literature has recently investigated price processes that violated the Ito process. Christensen, Oomen, and Renò (2022) investigates the occurrence of short-lived locally explosive trends in the price pathways of financial assets, whereas Andersen, Todorov, and Zhou (2023) proposes a detector involving violations of the usual Ito semimartingale assumption. This study also discovers the intraday return point violating the ito process of the Black-Scholes model and demonstrates its background mechanism by employing the breakeven range of Greek PnL in the option book. In addition, since Jegadeesh and Titman (1993) documented abnormal returns from the strategy of long winners and short losers, research on market momentum has expanded to encompass a broader range of asset classes and countries.[6] Recently, there has been a growing body of literature focusing on intraday momentum. Studies such as Heston, Korajczyk, and Sadka (2010) explore the intraday predictability of cross-sectional returns, Gao et al. (2018) document intraday momentum trends, and Li, Sakkas, and Urquhart (2021) analyze intraday time-series momentum. This paper adds to this literature by documenting one of the major sources of intraday abnormal returns under an option-related condition within the context of MMs' inelastic demand.

Secondly, asset price discovery using information from the derivatives market has been extensively studied due to its significance in determining asset prices. Poteshman and Pan (2004) find that information from option volume predicts stock prices. However, Muravyev, Pearson, and Paul Broussard (2013) argue that option price quotes do not provide useful information regarding future stock prices. Recent studies have expanded this literature by examining the impact of delta and gamma hedging on underlying prices. While existing literature mainly focuses on MMs' gamma imbalance position, this study contributes by identifying the triggering range of gamma hedging derived from MMs' inelastic demand created by the book PnL.

Thirdly, the literature on asset price discovery by intermediary participants has been growing. He and Krishnamurthy (2013) find that risk premia rise when intermediaries face capital scarcity, emphasizing the importance of intermediaries' actions. This paper supports this argument by showing how the gamma loss over theta profit could potentially trigger capacity scarcity for intermediaries. Additionally, this paper contributes to the literature on demand system-based asset pricing. While previous studies demonstrate that inelastic demand from passive institutions influences asset prices, this work shows that MMs' inelastic demand, created by PnL restrictions, impacts intraday asset prices, and it's more pronounced when active institutions have demands in those options. Furthermore, the discovery of the GTBR and its significance have practical implications. Firstly, it can aid market participants in decision-making. Secondly, the GTBR can serve as an important threshold for firms or regulators to assess risk management metrics dynamically, based on option-implied information, which is particularly useful in fast-changing financial market conditions. Thirdly, the frequency of breaking this range can be utilized to estimate MMs' OI limit

[6]Griffin, Martin, and Ji (2001) demonstrate the economic significance of global momentum profits. Additionally, various scholars have investigated different sources of momentum. For example, Hong, Lim, and Stein (1998) examines the effects of size and analyst coverage on momentum, while Moskowitz and Grinblatt (1999) identify the industry component of stock return momentum.

or underlying market capacity.

In the following Section 2, this paper explains in detail the process of delta-neutral hedge managing short gamma to maintain a delta-neutral position during a day, as well as the profile of gamma PnL versus theta PnL. The article then elaborates on why the break-even range is crucial for delta-neutral traders like MMs and its importance as a threshold for intraday momentum. Section 3 outlines the data sources for empirical testing and the methods used for data cleansing. In Section 4, the empirical analysis of the break-even range is discussed.

2 Inelastic Demand and Gamma-Theta Breakeven Range (GTBR)

This section provides a detailed explanation of how inelastic demand in short gamma hedging relates to GTBR before showing the testing results. Starting with the review of the dynamic hedge to understand the circumstance which option MM faces upon carrying short gamma imbalance in Section 2.1, Section 2.2 use an example of MMs' gamma hedge to explain the motivations behind delayed delta rebalancing (for the rest of the paper, gamma hedge and delta rebalancing are used interchangeably). Section 2.3 explains how to find the GTBR and when the underlying stock price hits the GTBR, inelastic demand for the underlying stocks arise.

2.1 Dynamic hedge review

This subsection reviews the source of the gamma PnL when the delta-neutral trader sells a call option with a relevant delta-neutral hedge. Since Black and Scholes (1973) developed the option pricing model, the option pricing method based on the dynamic hedge has been widely used by options traders and serves as a valuable guide for market makers (MMs) who provide liquidity in the options market by replicating options payoff.[7]

[Insert Figure 1 here]

Figure 1 represents an example case where MMs have a short call option with their delta hedge position by the underlying price at 103. The blue line is the typical option value payoff that MMs

[7]This pricing concept facilitates option traders buying or selling options from other market participants because they can hedge their long or short option position by trading their underlying assets so that they can maintain their entire portfolio risk at a neutral level. For example, if MMs sell a call option, then they buy some delta shares of its underlying asset to match the change in call option value.

should replicate (so their target payoff to replicate). The delta hedge replication (gray line) has a linear payoff as its price rises. The delta hedge performance, however, is unable to keep up with the convex value growth of the option. That is, as the underlying price rises, the slope (delta) of the option value grows while the hedged asset value remains linear. This is known as the gamma effect. Therefore, MM needs to rebalance (buy more) the delta at 106 to match the higher delta requirement, and this value gap is a gamma loss (red line) in Figure 1(a). On the other hand, as time passes, the option value decays, as shown in Figure 1(b) (green line). Figure 1 shows not only a trade-off between the gamma and theta PnL but also the crucial implication that the theta PnL for a day is somewhat static while the gamma PnL, its counterpart, varies by the underlying movement. This fact is more clear in Figure 2

[Insert Figure 2 here]

Figure 2 shows a PnL profile of a delta-neutral trader carrying a short gamma position during a day starting with a spot price of 105. Total PnL (=Theta PnL (green line) + Gamma PnL (red line)) is the highest at 105, while it reduces exponentially if the spot price moves in either direction. If the spot price moves more than this range of the yellow lines where the total PnL begins negative, then the delta-neutral trader faces an unfavorable position and is more likely to delta-hedge to stop losing money. This total PnL change comes from the heterogeneity of the payoff between the option and the option hedge instruments. The option value changes continuously and non-linearly with convexity. On the other hand, its hedge instrument (underlying stock or future) value changes linearly. Therefore, while a large upward or downward movement changes option values non-linearly, the underlying value of the hedge only moves linearly and does not catch up with the convex movement of the option.

It would be ideal if the gamma loss equals or is less than the theta gain (the spot price is inside the yellow lines) because it means that the implied volatility turns out to be the same as the realized volatility. This is an important assumption of the Black-Scholes option pricing model. In reality, however, realized volatility changes frequently and moves more or less than the assumption, and rebalancing always has costs associated with it as well shown in FIGLEWSKI (1989). As a result, numerous studies have been conducted to identify an optimal delta hedge strategy or to derive an optimal option pricing model.[8] Because of the model limitation, hedge traders' discretion in managing option portfolios is often required, which can adversely affect underlying prices having an intraday market impact, as shown by Baltussen et al. (2021). Table 1 in the following subsection provides an anecdotal example of a case that a typical hedge trader faces on a daily basis. [9]

2.2 An example of intraday hedging dynamics

This subsection shows four typical cases that a delta-neutral trader, such as a market maker (MM), faces during the day when they have an open short gamma position. Through table 1, this paper draws attention to the challenge of the short gamma hedge and shows that the gamma hedge decision is complex, affected by the limitation of option pricing models and the hedger's incentive to maximize PnL rather than a pure risk management perspective.

[Insert Table 1 here]

Table 1 shows that a MM, a typical delta-neutral trader, sold call options and bought delta shares of the underlying assets to hedge and replicate the short call position at the market close with the following details: Underlying price: \$100, Strike price: \$100, Days to expiry: 30 days, Interest rate: 3%, Notional amount: \$10 million (mio), Volatility: 22%. This option opens the following Greeks, Delta: 0.539, Gamma: 0.046, Theta: -0.061. On the following market day, suppose that the underlying stock goes up by 1%, 180 minutes after the market opens. Then, assuming all other Greeks remain fixed, the dollar delta from the short option position will increase from \$5.38 mio to \$6.00 mio while the dollar delta from the long stock position will almost stay at \$5.38 Mio. As a result, the net delta of the two positions is -619.01k. If the stock does not move but stays at +1% until the market closes, then the MM must buy \$619.01k of the underlying at +1% higher price, which locks up \$3.1k gamma loss. Instead, the MM earns \$6.11k in theta profit as compensation for the gamma loss.

[8] For example, the stochastic volatility model has been studied since Heston (1993). On the other side, sticking with the Black-Scholes model, Hull and White (2017) examines the minimum variance delta method, considering the effect of underlying price change on implied volatility.

[9] Profit and loss (PnL) attribution of Carr and Wu (2020) has been simplified by assuming that 1) the vega PnL is negligible because gamma exposure is large at relatively shorter maturity with smaller vega exposure and implied volatility during the day does not change very frequently, unlike realized volatility; 2) portfolio delta is hedged to be neutral; and 3) funding PnL is very tiny during the day. As a result, the portfolio's PnL attribution during the day considers gamma and theta profiles as well as intraday trading. Appendix A has a detailed formulation of this simplification.

Case 1 shows that the underlying moves up +1% at 180 minutes (T_180m) and back down to flat at 390 minutes (390m) while MM does not take any action for the day. Then, this would be the best scenario for MMs' current short gamma position because MMs' total daily PnL will be +6.11k and MM does not have to take any action. However, after 180m, if the underlying rises up further to +2% as in Case 2, then MMs' gamma loss would increase to -12.08k, which is greater than its theta profit (+6.11k). Therefore, MM must decide whether to begin rebalancing before the market closes so as to compensate for its gamma loss by trading PnL. Case 3 is an ideal example of early rebalancing since its total PnL ends up with +0.22k. However, for uninformed delta-neutral traders, this decision-making is tricky because if MMs' decision is incorrect, then the decision will result in trading loss, as in Case 4. In comparison to Case 1, which has the same underlying stock scenario, Case 4 loses all of the theta gains due to early delta rebalancing. This uncertainty leads MM to refrain from early or frequent reactions to the gamma hedge. This difficulty intensifies greatly when they have a large position, necessitating deeper investigation of their dynamics in conjunction with underlying asset impact, as Bates (2003) emphasizes the necessity for renewed attention on the financial intermediation of underlying risks by option market makers.

This challenge stems not only from the difficulty of forecasting future volatility but also from a trader's incentive to maximize theta profit over gamma loss when they carry a short gamma position. As proved by Odean (1998), investors carrying losing trades hold it longer while others carrying winning trades hold the position shorter. Their behavior with the hope for market reversion for maximizing theta gain over the gamma and their demand for reducing hedge costs from frequent hedging work against the firm's risk management goal. This environment supports that hedgers are demotivated to frequently hedge, and the inelastic demand for hedgers is not created when the underlying stock price is in the GTBR. On the other hand, when total PnL turns negative, an inelastic demand to trade underlying asset arises.

2.3 Delta-neutral trader's incentive on gamma-hedging at the gamma-theta breakeven range (GTBR)

This section shows that the delta-neutral trader's incentive to maximize profit leads them to gamma-hedge (delta-rebalancing) at the gamma-theta breakeven range (GTBR). First, Section 2.3.1 derives the gamma theta breakeven range (GTBR). Section 2.3.2 derives the hedge triggering point of the delta-neutral trader based on their profit-maximizing incentive. Lastly, Section 2.3.3 shows that the GTBR from Section 2.3.1 is a special case of the hedge triggering point from Section 2.3.2. Through these steps, this study finds that the hedge trader's incentive to maximize PnL leads to the hedge trigger point close to the GTBR.

2.3.1 Deriving the gamma-theta breakeven range (GTBR)

The example in Section 2.2 shows a delta-neutral trader's challenge in replicating the option value because gamma PnL is not always perfectly compensated by theta PnL. In other words, the total PnL of gamma and theta fluctuates with the intraday market movement. This PnL fluctuation can affect the delta-neutral hedge trader's incentive or willingness to gamma hedge. Therefore, when a delta-neutral trader opens gamma exposure, the breakeven range between gamma PnL and theta PnL (GTBR) is its turning point of the daily PnL and serves as an important reference for their discretion on rebalancing delta in a direction of the market momentum. Since Baltussen et al. (2021) and S. X. Ni, Pearson, Poteshman, and White (2020) argue that hedging short gamma exposure creates intraday price momentum, it is also important to test whether the GTBR acts as an inflection point where the gamma hedge impact begins or accelerates. Assuming other Greeks and their PnL are fixed, by using the PnL attribution of Carr and Wu (2020)[10], the delta-neutral trader's PnL from gamma and theta exposure for a day at market close, T, from an option is

$$PnL_T = \frac{\theta}{365} + \frac{1}{2}\Gamma \cdot 100 \cdot r \cdot r = \frac{\theta}{365} + 50\Gamma \cdot r^2$$

Let $r = GTBR$, and $PnL = 0$. Then,

$$GTBR = \pm\sqrt{-\frac{\theta}{365 \cdot 50\Gamma}} \tag{1}$$

The term Γ represents the dollar gamma, which is the change in the dollar delta for a 1% change in the underlying asset's price. It is calculated as $\Gamma = \frac{\gamma S^2}{100}$, where γ is the Black-Scholes Gamma, and S denotes the price of the underlying asset. The symbol θ stands for Theta, and r represents

[10] See also Cont and Tankov (2010) and Bergomi (2015).

the percentage change in the underlying price for a day.

2.3.2 Hedge trader's perspectives: Optimum gamma hedge point

This subsection finds the optimal hedge trigger point for a trader's perspective by using their profit-maximizing incentive. The delta-neutral trader decides whether to rebalance the portfolio delta to neutral at a specific time during the day. The decision would follow their expected PnL into the close with their rebalancing impact. The trader's expected PnL for the day at a time, t, is

$$E_t[PnL_T] = E_t[50\Gamma r_{T-t}^2 + 50\Gamma r_t^2 + \theta_1 + H\{(r_{T-t} - 100k\Gamma r_t)(-100\Gamma r_t) - |100\Gamma r_t \cdot tc|\}|r_t] \quad (2)$$

The term r_T represents the percentage change in the underlying price at the market close. H indicates whether a hedge trader rebalances during the day, with a value of 1 if rebalancing occurs and 0 otherwise. The symbol t refers to the timing of when a hedge trader rebalances. The term θ_1 represents Theta for one day, calculated as $\theta_1 = \frac{\theta}{365}$. The variable k denotes the trader's expected market impact relative to the trading dollar size. Finally, tc stands for the transaction cost, expressed as a percentage.

The trader's expected PnL for the day at t consists of the expectation of five components, the gamma PnL between the end of the day and a time of the day ($50\Gamma r_{T-t}^2$); the gamma PnL by the time of the day ($50\Gamma r_t^2$); the daily theta PnL (θ_1); the trading PnL from gamma-hedge (delta rebalancing) considering its market impact ($(r_{T-t} - 100k\Gamma r_t)(-100\Gamma r_t)$) where $(-100\Gamma r_t)$ is the gamma hedge size upon r_t movement of the underlying; and the transaction cost ($|100\Gamma r_t \cdot tc|$). F.O.C for $E_t[PnL_T]$ by r_t, r_t^* is

$$r_t^* = \frac{\mu(T-t)(1 + 100\Gamma k) + tc'}{(1 + 2 \cdot 100^2 k^2 \Gamma^2)} \quad (3)$$

The details of the derivation are in Appendix A2. r_t^*, the gamma hedge triggering level at t varies depending on the remaining time for the day, the expected average return from a hedger, the impact cost, and the transaction cost. The gamma hedge will be triggered at the wider range if the remaining market hour is longer or if return drift, potential market impact, or transaction cost is higher.

2.3.3 Relation between GTBR and gamma hedge triggering level

From equation (1) in Section 2.3.1, GTBR is derived and can be simplified as below. The detailed step for the simplification is in the Appendix A3. Also, from equation (3) in Section 2.3.2, this gamma hedge condition can have the same level as GTBR under the condition: before the market open ($T - t = 1/365$), no impact and cost ($tc' = k = 0$), and a hedger believes the underlying may move as the implied volatility.

$$GTBR \approx \pm\sqrt{-\frac{\theta}{365 \cdot 50\Gamma}} = \pm\frac{\sigma_{imp}}{\sqrt{365}} \approx E[r_t^*] \tag{4}$$

The delta-neutral trader's gamma hedge triggering condition would be close to the GTBR before the market opens if the hedger's belief in average daily return is close to the daily variance. Therefore, r_t^*, the gamma hedge triggering level of the daily return at t, can be a more general condition of the GTBR. Before the underlying market opens or if the market does not move at all, a delta-neutral trader such as MM would use the GTBR as a benchmark reference level for their decision-making, and this reference range can be adjusted depending on the dollar gamma amount, its potential market impact relative to liquidity, its hedge timing, and overall reference daily return. Section 4 empirically demonstrates the significance of this range, the GTBR, as an inflection point at which the intraday momentum by delta-neutral traders impacts the intraday momentum. The data set used for the empirical analysis is introduced in Section 3.

3 Data

This paper hypothesizes that the intraday momentum driven by the option hedge demand is limited or accelerated under the special condition because the delta-neutral hedge trader does not always decide to follow the trend in every case. Therefore, this empirical testing requires a dataset to measure the underlying intraday performance, the demand for gamma hedge, and the GTBR. The following subsections describe the source and the cleansing method of the data. Appendix B1 also has the descriptive statistics of the data.

3.1 Underlying Intraday Performance: TAQ

The intraday performance of the underlying is measured by the relative return during a day. Those returns are calculated by using the mid of the best bid and the best ask quotes for every minute. This paper follows the measure of the intraday market momentum by Gao et al. (2018)'s approach using half-hour observations of a day. Baltussen et al. (2021) also show the intraday momentum from the gamma hedge by regressing the last 30 minutes performance by the first 30 minutes performance.

$$r_{i\_j} = \frac{Midqoute_i}{Midqoute_j} - 1$$

Where Midquote_i is the midquote of i minutes after the market opens for $i = 1, 2, \ldots, 390$, and Midquote_0 is the closing price of the most recent market day. The Monthly Trade and Quote (MTAQ) from SAS Cloud of Wharton Research Data Services (WRDS) are used to measure intraday midquotes. MTAQ data are cleaned by Holden and Jacobsen (2014)'s interpolated time technique which alleviates some distorted measures of spreads driven by high-frequency quotes to replicate Daily Trade and Quote (DTAQ).

3.2 Demand for gamma hedge: ISE

Delta-neutral traders' demand for gamma hedge in an underlying on a day is a function of the dollar gamma positions carried by them. That dollar gamma position is the summation of each dollar gamma position from all options listed for the underlying. Estimating the dollar gamma position of the delta-neutral trader at each underlying for each day is a difficult task because the trading volume and open interest (OI) data available publicly do not specify an investor group or their purpose for positioning. Nevertheless, their position can be estimated fairly accurately by using the fact that MM is one of the most representative delta-neutral traders. MMs' daily position is estimated from the daily open and close position data provided by the NASDAQ International Securities Exchange (ISE). ISE data includes 'Opening Buy/Sell' and 'Closing Buy/Sell' quantities for 'Firm,' 'Customer,' 'Broker/Dealer,' 'Proprietary,' and 'Professional Customer' levels. The difference between the total buy and total sell per day is their daily net trading quantity. For

'Firm' on the day t, net daily trading quantity of the option i of an underlying is

$$FirmNetTradQty_{t,i} = OpenBuy_{t,i} - OpenSell_{t,i} + CloseBuy_{t,i} - CloseSell_{t,i}$$

The cumulative sum of each option from its listing date is the open interest (OI). For 'Firm' by the day T after the option i's listing date, the open interest of the option i of the underlying is

$$FirmOI_{T,i} = \sum_{t=1}^{T} FirmNetTradQty_{t,i}$$

The next step is to find the MMs' OI based on the OI of 'Firm', 'Customer', 'Broker/Dealer', 'Proprietary', and 'Professional Customer'. This paper follows the approach of S. X. Ni et al. (2020). It estimates the total MMs' OI by the sum of 'Firm', and 'Customer' OI multiplied by -1.

$$MM\_OI_{T,i} = -1 \cdot (FirmOI_{T,i} + CustomerOI_{T,i})$$

This method assumes that MMs' usual counterparties are 'Firm' and 'Customer' accounts. This assumption is reasonable, and it allows this test to yield more conservative results. One might argue that some of the 'Firm' or 'Customer' are also delta-neutral traders, as is MM. However, in this case, if MM has a short gamma, the other party is likely to have a long gamma position. If the empirical test of MMs' short gamma position reveals significant results despite the presence of long gamma delta hedgers (which mitigate the short gamma effect) at the counterpart side, the original argument that the short gamma delta hedge has a significant impact on market intraday trend will be strengthened. [11] Therefore, MMs' dollar gamma position for a day T for the 'option i' of the underlying is

$$MM\_\Gamma_{T,i} = MM\_OI_{T,i} * \frac{\gamma_i \cdot MidQoute_T^2}{100} \cdot ContractSize$$

[11]Some literature estimates MMs' OI by put option OI based on the assumption that MM has counter positions against heavy put option demands from end-users. Gârleanu, Pedersen, and Poteshman (2005) prove it for OTM put options thanks to the special data identifying aggregate positions for dealers and end consumers. However, given that the gamma position varies by strikes and is exponentially high at ATM, this assumption is not perfect. Hence, using ISE data, which identifies the OI by groups, provides a more accurate estimate of the MMs' gamma exposure.

where γ_i: Black-Scholes gamma for the option i. Also, MMs' dollar gamma position for a day T for the 'underlying' is

$$MM\_\Gamma_T = \sum_{i=1}^{I} MM\_\Gamma_{T,i}, \qquad i = \{1, 2, ...I\}$$

At this stage, MMs' estimated gamma position for each underlying for each day is added in a new column to the dataset from the previous section. [12]

3.3 Gamma-Theta Breakeven Range: OptionMetrics

GTBR can be calculated in two ways, as shown in Sections 2.3 and 2.5. Both methods should produce nearly identical statistics. [13] GTBR can be calculated for each option because a GTBR is determined by each gamma and theta Greek of each option, respectively. Because there are multiple options with multiple strikes and tenors for each underlying, the most accurate estimate of the average GTBR for each underlying for each day would be calculating MMs' dollar gamma weighted average to each underlying for each day. Instead, as reference Greeks and volatility, this paper employs the at-the-money (ATM) with 30 days tenor option from the Standardized option data table in Ivy DB US of OptionMetrics. The OptionMetrics' Standardized Option data are ATM forward options with interpolated tenor from fixed expiry. They are widely used for empirical testing due to their convenience and representativeness. This simplified approach assumes that ATM option with 30 days tenor as a representative option structure in measuring the gamma impact because 1) ATM gamma and theta are exponentially higher than other longer strikes; 2) there's only a minor gamma effect from far OTM and deep ITM options in both downside and upside; 3) due to volatility skew, relatively small GTBR difference from higher volatility in downside and lower volatility in upside would even be averaged out; 4) longer tenor options do not have much gamma but mostly used to build a vega position; and 5) using 30 days standardized tenor would result

[12] The first 250 days of the data for each underlying are deleted based on the assumption that the first row of the cumulative OI data window does not include previous cumulative data. For example, if the first row of the OI data for an underlying is on 2 January 2006, then the cumulative sum of OI on 2 January 2006 does not include the cumulative data of the previous year. The best estimate would be to find its relevant listing date and filter out the biased data. However, for convenience and simplicity, the current version of the analysis assumes that the significant net open trade began a year ago cumulatively. Therefore, the first 250 days (approximately a year) of the cumulative data are removed as they can be biased. Then, 1% and 99% of the outlier are winsorized.

[13] Their means are 0.02101 and 0.02063 while both standard deviations are 0.01138. The empirical analysis primarily uses the 2.3 method.

in a more conservative effect in this empirical analysis purpose.[14] Therefore, using Greeks and volatility from the ATM option with 30 day tenor is an excellent reference for Greeks and volatility in measuring the impact of gamma hedges. At this stage, daily GTBR data are calculated and added in new columns to the dataset of the previous section.

4 Empirical Analysis

This section tests various hypotheses to unveil the impact of MMs' gamma hedging on the intraday momentum of the underlying asset, particularly through their inelastic demand at the GTBR. Sections 4.1 to 4.5 demonstrate the existence of intraday momentum, which becomes pronounced when the underlying price hits the PnL-driven range, GTBR. In Sections 4.4 to 4.7, this study looks at a subset of observations and the source of the gamma position. It shows that MMs' inelastic demand has a big effect on momentum when active investors buy options, especially when the underlying asset goes down and when they carry short gamma from downside strikes. The subsequent sections assess whether this result stems solely from expiry impact and confirm the validity of the momentum impact at the GTBR through out-of-sample R-square analysis.

4.1 Does Impact of Gamma Hedge Rise at GTBR?

By regressing the last half-hour return, r_{390_360}, on the first half-hour return r_{30_0}, Gao et al. (2018) reveals an intraday momentum pattern. Utilizing this methodology, Baltussen et al. (2021) demonstrates that the market's intraday momentum exists significantly more prominently on days with negative Net Gamma Exposure (NGE). This section tests the hypothesis that the hedge impact of delta-neutral traders on intraday momentum is pronounced at GTBR where their total PnL turns to negative and inelastic demands arise. In other words, the test hypothesizes whether the GTBR being broken or not during a day is an important inflection point for intraday momentum. Indicator variables are introduced to test it. At time t, $D\_GTBR\_Hit_t$ is set to 1 if the intraday return breaks over GTBR, and 0 otherwise. The variable D_Short_Gamma is set to 1 if the market maker carries a negative dollar gamma position from the previous day and 0 otherwise. The following regressions

[14] Besides, small error of the reference volatility impact is minimal as $GTBR = \frac{\sigma}{\sqrt{365}}$.

test the hypothesis that at GTBR, intraday momentum is accelerated.

$$r_{390\_360} = \alpha + \beta_1 \cdot r_{30\_0} + \beta_2 \cdot r_{30\_0} \cdot D\_Short\_Gamma + \beta_3 \cdot r_{30\_0} \cdot D\_GTBR\_Hit_{360} + Controls$$

Earnings and implied volatility control interacted with r_{30_0} are added to the regression (5).

[Insert Table 2 here]

Table 2 represents the result of the regression for the last 30 minutes' return by the first 30 minutes return. The result uses Newey and West's (1986) t-statistics, and all coefficients are multiplied by 100. The firm-level fixed effect is applied. The regression in column (1) shows that there is intraday momentum, as proven in the earlier study by Gao et al. (2018). Additionally, the regression in column (2), including D_Short_Gamma, reveals that the short gamma sign has a substantial explanation for market intraday momentum, as shown by Baltussen et al. (2021). Column (3), including $D\_GTBR\_Hit_{360}$, demonstrates that breaking GTBR is also a significant factor. Finally, column (4), including both D_Short_Gamma and $D\_GTBR\_Hit_{360}$, shows that this breaking range impacts intraday momentum beyond the short gamma impact. This result implies that the intraday stock momentum of the underlying is also accelerated at GTBR, and the creation of inelastic demand by its PnL restriction between gamma profit and theta loss triggers underlying delta rebalancing and contributes to intraday momentum. Regression (5) adds two controls, the earning impact, and implied volatility impact, which interact with r_{30_0}. $D\_Earning$ equals one if an earning is announced 24 hours before the 360th minute of a day and zero otherwise. The result shows that the coefficient of the main variable, $D\_GTBR\_Hit_{360}$, even increases from 0.96 to 1.18 with larger t-statistics. On the other hand, the control variable, earnings announcement impact on intraday momentum, shows a negative coefficient of -2.41, indicating that it works as an intraday reversion force. This result is in line with Milian (2015)'s findings that earnings announcements have a negative correlation with price action for firms with active listed options. The second control variable, implied volatility, shows a strong and significant impact on intraday momentum, and it subsumes the impact from the momentum coefficient r_{30_0} and the gamma impact, $D\_Short\_Gamma \cdot r_{30\_0}$ because of high correlations, 89%. On the other hand, the GTBR coefficient is robust even after adding those control variables. In general, after adding controls, $Adj.R^2$ increases a lot.

This analysis has the limitation that $D\_GTBR\_Hit_{360}$ lacks cumulative information on breaking GTBR and only considers the price location at a specific time. However, psychological factors guiding traders' expectations for the rest of the market hour would be influenced by the past history of intraday and its cumulative status, potentially influencing the elasticity of demand. For example, hitting GTBR at only the 360th minute of the day would be very different from hitting GTBR for every minute by the 360th minute during the same market day. Also, this analysis raises the question of whether the market intraday momentum is still valid even in cases where the MM has relatively smaller short gamma or even long gamma exposure. The next section, therefore, examines market intraday momentum by dollar gamma exposure quintiles and by cumulative GTBR hit numbers.

4.2 Does Cumulatively Breaking GTBR and Gamma Size Impact Intraday momentum?

This section analyzes the cumulative effect of breaking GTBR and the effect of gamma size by sorting data. To achieve it, the cumulative effect of breaking GTBR is first measured by the cumulative sum of the past number of breaking GTBR at every minute:

$$Cumul\_GTBR\_Hit_t = \sum_{m=1}^{t} D\_GTBR\_Hit_m$$

The data is then classified into groups as 0, 1 to 89, 90 to 179, 180 to 269, 270 to 359, and 360 times the number of breaking GTBR for 360 minutes. Next, the dollar gamma size is normalized by the average of the last seven days of the underlying volume multiplied by the $MidQuote$. The data is then sorted by quintile:

$$NormGamma_t = \frac{\Gamma_t}{MidQuote_t \frac{1}{7} \sum_{d=t-6}^{t} V_d}$$

[Insert Table 3 here]

Table 3 shows the results of the regression identifying the intraday momentum by sorted groups of data, and its result shows why both short Gamma and GTBR are important in Table 2. The first column $NormGamma^1$ shows the regression result from the data having the largest short gamma exposure, while the last column $NormGamma^5$ shows the regression result from the data having the largest long gamma exposure. The first row ($Cumul\_Hit\_GTBR = 0$) represents the regression results from data with non-breaking GTBR for 360 minutes, while the last row ($Cumul\_Hit\_GTBR = 360$) shows the regression results from data with 360 times of breaking GTBR for 360 minutes. The result of the first row shows the regression results of the data where the underlying market has never broken the GTBR, and there is no significant intraday market momentum despite the case that the MM has the highest short gamma in the first column. This evidence explains that the GTBR is a significant factor in determining the intraday momentum. Furthermore, the last column explains that when the MM carries the highest long gamma, there is a significant market intraday 'reversion' (-1.25). This implies that MMs' long gamma position pushes back the intraday movement to reverse as a contrarian when the underlying market is quiet. Besides, in other cases where the GTBR is hit more frequently, there is no clear intraday momentum and reversal but a mild intraday reversal. From the rows with the cases ($1 \leq Cumul\_Hit\_GTBR \leq 359$), and from the columns where the MM carries a short gamma position, the data discover that the GTBR being hit has more intraday momentum than zero hits. Interestingly, the last row has a significant but weaker coefficient (relatively weaker intraday trend) than other rows ($1 \leq Cumul\_Hit\_GTBR \leq 359$). Because the market already opens and stays out of the GTBR for the entire day, MMs' delta hedge from gamma exposure is spread out over the day rather than concentrated in the last 30 minutes. The whole results imply that beyond literature, the short gamma exposure sign or size is not what solely determines the gamma impact, but without hitting the GTBR, there is no short gamma impact, and this impact is somewhat monotone on the degree of hitting the GTBR. In Appendix D, this case is reviewed again with the same regression setup but the data with the cumulative number of the whole day rather than the cumulative number of the day by the last 30 minutes.

4.3 Momentum Coefficients in Groups by GTBR-Normalized Return

This section tests the momentum coefficients of groups by GTBR-normalized return to show the effect of hitting GTBR graphically. To prepare the analysis, the absolute returns at the 360th minute are normalized by its GTBR:

$$GTBR\_Normalized_{360} = |\frac{r_{360\_0}}{GTBR}|$$

For example, if the absolute return at the 360th minute is 0.50% while the GTBR is 1.00%, then this normalized return is calculated to be 0.50. Then, these data are sorted and grouped by deciles. For each decile, regressions with the dependent variable, r_{390_360} and the independent variables, r_{30_0} and $r_{30\_0} \cdot D\_Short\_Gamma$, are executed. The coefficient of the independent variable, r_{30_0}, which is the momentum coefficient, is estimated for each decile.

[Insert Figure 3 here]

Figure 3(a) shows the coefficients of each decile. The data point at which this normalized return equals 1 (the return at the 360th minute = GTBR) is located at the 67.7% percentile and is represented by an orange vertical line. Figures 3(b) and (c) represent the same chart, but the data are divided by the sign of the return for the first 30 minutes. In all cases, decile 1, where stocks do not move much at all at the 360th minute, does not show any momentum but reversion. The momentum coefficient clearly increases as the decile increases and jumps around the percentile where the return at the 360th minute equals the GTBR (between decile 6 and 7). This evidence supports the argument that the gamma hedge activity around the GTBR boosts the market's intraday momentum. Besides, the coefficients begin decreasing after decile 7. This reduction potentially comes from the case that MM already rebalanced its delta exposure at GTBR earlier. Hence, it does not force the delta-neutral trader to push the intraday momentum for the last 30 minutes. For example, the average of normalized returns in decile 10 is 2.51 (2.51σ), which is significantly far from the GTBR (1σ). Therefore, in this case, the gamma hedge activity would have been done earlier or spread over the day, as in the case of $Cumul\_Hit\_GTBR_{360}$ in Table 3 of Section 4.2.

4.4 Momentum Influence from Active Investor Demand via MM Channel

Koijen and Yogo (2019) proposed an asset pricing model with asset demand among investors, aiming to reflect institutional demand patterns and clarify institutional roles. While their study focuses on the inelastic demand from passive institutions by utilizing open interest data of active investors, this section delves into how the inelastic demand of MM is associated with option demand from active investors. The ISE introduced a new trade category on October 1, 2009, termed 'PROFESSIONAL CUSTOMER'. This category refers to market participants who, not trading for MM or firm accounts (like banks), enter over 390 orders per day across a month. These positions typically represent active institutional demands such as hedge funds, active mutual funds, boutiques, etc.. Table 5 illustrates the examination of whether intraday momentum on an underlying asset varies when active investors engage in the options market for that asset.

[Insert Table 5 here]

$Prof\_Option\_Holding = 1$ if the professional investor's option open interest is positive and 0 otherwise. The column (6) - (3) indicates the coefficient difference with Walt statistics following chi-squared distribution. The difference between (3) and (6) shows that the intraday momentum impact from MM upon hitting the GTBR is notable when professional investors hold long option positions in the same underlying asset. This supports the notion that active institutional demand channels through the option market, thereby creating inelastic demand through option MM. On the other hand, the results of (1) and (4) show that the intraday momentum impact explained by the gamma position does not exist when professional investors engage in the options market. This also bolsters the inelastic demand created by PnL restriction, which explains intraday momentum rather than the gamma position itself, which was widely used in previous literature.

4.5 Don't They Buyback Options Rather Than Gamma Hedge in Underlying Asset?

When MMs carry a short gamma position and the GTBR is hit, it's natural to assume that the MMs may buyback their option positions, as there might be no need to hedge inelastically. Table 4 presents the testing results of the hypothesis that MM buy back options when the underlying asset moves over the range frequently (in other words, the underlying return hits GTBR frequently). The dependent variable is an open interest of MM for a day, denoted as $MM\_OI_{T,i}$, and it's regressed by the frequency of hitting the range. The same regressions are conducted on four different subsets grouped by sign of gamma position and direction of underlying asset return.

[Insert Table 4 here]

The results indicate that when MMs carry short gamma positions, upon frequent hitting of the GTBR (meaning that there is a greater chance that the hedger has more restricted times in terms of PnL perspective and so a greater chance that inelastic demand arises), they do not buy back or sell options. This suggests that to keep their delta-neutral position flat, they have to conduct dynamic hedging by trading the underlying asset. This bolsters the argument that MMs' delta rebalancing hedge has an intraday momentum impact because they do delta hedge rather than buying back those sold options. On the other side, when MM has long gamma positions, they frequently buyback more options in response to GTBR triggers. If they expand their holdings of options with long gamma exposure, they should further hedge their long gamma positions by contrarian trades in contrast to momentum trades from short gamma positions. This behavior supports the findings in Table 3, which imply that when maintaining long gamma positions, there is no momentum in the underlying asset.

4.6 Heterogeneous Impact of Gamma Hedge on Intraday Momentum Based on Underlying Return Direction

This section conducts a similar regression to Section 4.1 but divides the data into two groups to explore whether the GTBR behaves differently depending on the underlying return direction. The first group comprises data where the underlying stock moves up 30 minutes after opening, while the second group includes data where the underlying stock moves down 30 minutes after opening.

[Insert Table 6 here]

Table 6 presents panel (a) for the moving-up case of underlying asset return and panel (b) for the moving-down case of underlying asset return. The results indicate that intraday momentum exists in both directions. However, in panel (a), both interaction variables in regression (3) and (4) are insignificant, while in panel (b), these interaction variables are significant. This suggests that the contribution to intraday momentum from short gamma and breaking the range is more pronounced when the underlying asset moves downward asymmetrically in the first 30 minutes. Moreover, breaking GTBR holds stronger significance and effect on intraday momentum than the gamma position does. This finding also underscores that the gamma hedge impact differs from the short-sale squeeze, which is only present in an upward direction. In addition, this tendency shows that the inelastic demand which comes from PnL restriction comes more strongly during the downward movement of the underlying assets.

[Insert Figure 4 here]

The result is further illustrated in Fig 4, which depicts the average intraday trend and compares them based on whether they have a short gamma, hit the ranges, or both. The green lines in (a) and (b), representing data hitting GTBR under short gamma positions, exhibit clearer intraday momentum than other cases without hitting GTBR. The yellow line, representing data with short gamma positions but without hitting GTBR, shows only slightly larger momentum than the blue line, which represents the raw case.

4.7 Heterogeneous Impact of Gamma Hedge on Intraday Momentum Based on Source of Gamma Positions?

This section replicates the regression from Section 4.6 but examines various sources of gamma positions, such as gamma positions from call options, put options, upside strike options, and downside strike options. Table 7 presents three panels: Table (a) includes all data, Table (b) includes data where the underlying asset rises in the first 30 minutes, and Table (c) includes data where the underlying asset moves down in the first 30 minutes. *D_Short_Gamma_Calls* (*D_Short_Gamma_Puts*) equals 1 if the market maker (MM) has a short gamma position from call (put) options, and 0 otherwise. *D_Short_Gamma_Upsides* (*D_Short_Gamma_Downsides*) equals 1 if the MM has a short gamma position from upside strike (downside strike) options, and 0 otherwise.

[Insert Table 7 here]

Panel (a) reveals that short gammas from calls, puts, and downside strikes contribute to the intraday momentum of the underlying market. This suggests that short gamma positions from both call and put options have a similar impact on intraday momentum. However, the strike range of the source of the short gamma position emerges as a crucial factor for momentum impact. Gamma positions from strikes above the underlying price show no impact on intraday momentum, while gamma positions from downside strikes exhibit a significant impact. The analysis extends to two subsamples, mirroring Section 4.6. Regardless of the underlying movement in the first 30 minutes, short gamma positions from call and put options significantly affect intraday momentum.

Additionally, the contribution to momentum from downside strike options is stronger during the first 30 minutes of the underlying market movement.

This finding supports the main argument of this paper that MMs' gamma position and hitting the breakeven range explain underlying intraday momentum more precisely. Short gamma positions from both short calls with long underlying and short puts with short underlying compel delta-neutral traders to trade the underlying instrument in the same direction as those of the underlying asset in their dynamic hedge activity. Thus, short gamma positions from both call and put options have a clear gamma impact on intraday momentum. Furthermore, the asymmetrical result between downside strike options and upside strike options suggests that delta-neutral traders have more inelasticity in demands for gamma hedge in downside movement scenarios when holding short gamma positions from downside strikes. This implies a need for increased discipline and risk management against the downside case of the underlying market when carrying short gamma positions from downside strikes.

4.8 Impact of Gamma Hedge on Intraday Momentum during Expiry and Non-Expiry Weeks

S. Ni, Pearson, and Poteshman (2005) illustrated that the hedge impact from option market makers tends to cluster around the expiration date at optionable strikes. As the option contract's duration shortens, the gamma imbalance of traders aiming to maintain delta neutrality becomes more evident. Consequently, the underlying stock price experiences increased volatility, attributed to the actions of delta rebalancing traders. Someone may argue that gamma hedge impact to intraday momentum just comes from strong expiry week data. To investigate this idea, this section conducts a similar test to Section 4.1, using a subset of data consisting solely of the expiry week and another subset of data excluding the expiry week.

[Insert Table 8 here]

The results depicted in Table 8 demonstrate that intraday momentum in the underlying market price is significantly present during both the expiry week and non-expiry weeks. This finding supports to the idea that hitting the breakeven range exerts a robust effect on the intraday momentum of the underlying asset return, regardless of whether it's during the expiration week or other time periods.

4.9 Out-of-Sample R^2

This subsection assesses the Out-of-Sample R^2 (OOSR2) to gauge the predictive capability of the GTBR. Given the inconsistency in the performance of factors, as noted by Goyal and Welch (2007), OOSR2, proposed by Campbell and Thompson (2008), has become widely adopted to evaluate out-of-sample predictability, aiming to mitigate the overfitting issue. Baltussen et al. (2021) and Gao et al. (2018) also employ OOSR2 to assess the intraday predictability in their analyses.

$$OOSR2 = 1 - \frac{\sum_{t=1}^{T}(r_{390\_360,t} - \hat{r}_{390\_360,t})^2}{\sum_{t=1}^{T}(r_{390\_360,t} - \bar{r}_{390\_360,t})^2}$$

A positive OOSR2 suggests predictability, indicating that the predictive model exhibits a smaller average mean squared error in prediction compared to the historical average. Following regression at each underlying level, the OOSR2s are computed.

[Insert Table 9 here]

Table 9 displays the summary statistics of R^2 and OOSR2 from regressions conducted for each underlying. Initially, the data are grouped by underlying, and then at each underlying level, the last 30 minutes' return is regressed on the first 30 minutes' return. Columns (1), (2), (3), and (4) represent different regressions for r_{390_360}, akin to Table 2. Column (1) features regression (1) with only r_{30_0}, column (2) adds D_Short_Gamma interaction to regression (1), column (3) adds D_GTBR_hit interaction to regression (1), and column (4) includes all variables. Underlying with fewer than 250 observations are excluded in this test. On average, R^2 and OOSR2 are highest in regression (4), which accounts for the GTBR effect combined with short gamma exposure. Moreover, all OOSR2 values are positive, with even the lowest OOSR2 from an underlying regression being positive. This suggests that the GTBR effect significantly contributes to prediction at each underlying level.

5 Conclusion

For the last decade, the volume of option delta-neutral traders such as option MM has been growing fast with the exponential growth of retail investors. Therefore, understanding their behavior and impact is crucial. This study provides a comprehensive analysis of the inelastic demand mechanisms of option MM and their effects on intraday asset prices. Through meticulous examination of MM behaviors, particularly those involving gamma and theta exposures, it has been elucidated how such exposures drive MMs' decision-making processes, influencing the broader market dynamics.

The empirical findings affirm the presence of specific breakeven points (GTBR) from gamma loss and theta profit, which serve as critical inflection points that intensify MMs' trading activities in the underlying asset. These points mark thresholds where market dynamics compel MMs to execute delta rebalancing trades, thereby creating inelastic demand for underlying assets. Moreover, the paper expands the discourse on demand-based asset pricing by incorporating the role of active institutions in shaping market conditions. Unlike previous research predominantly centered on passive institutional impacts, this study highlights how gamma imbalances of option MM created by active institutions (professional investors) contribute significantly to asset price movements. These findings contribute to a deeper understanding of how derivative markets influence underlying asset prices through delta and gamma hedging strategies. Furthermore, the study enhances our understanding of price discovery processes by documenting how violations of the Ito process can occur within financial markets, particularly under conditions influenced by options trading. This contributes to a nuanced comprehension of asset price dynamics and the pivotal role of financial intermediaries in these processes. The practical implications of this research are significant for both market participants and regulators. By identifying the breakeven points and their influence on market dynamics, this study provides valuable metrics for risk management and trading strategies. These insights can help firms and regulators formulate more effective policies and strategies on a real-time basis, particularly in fast-evolving market environments where the traditional models may not fully capture the complexities introduced by options trading.

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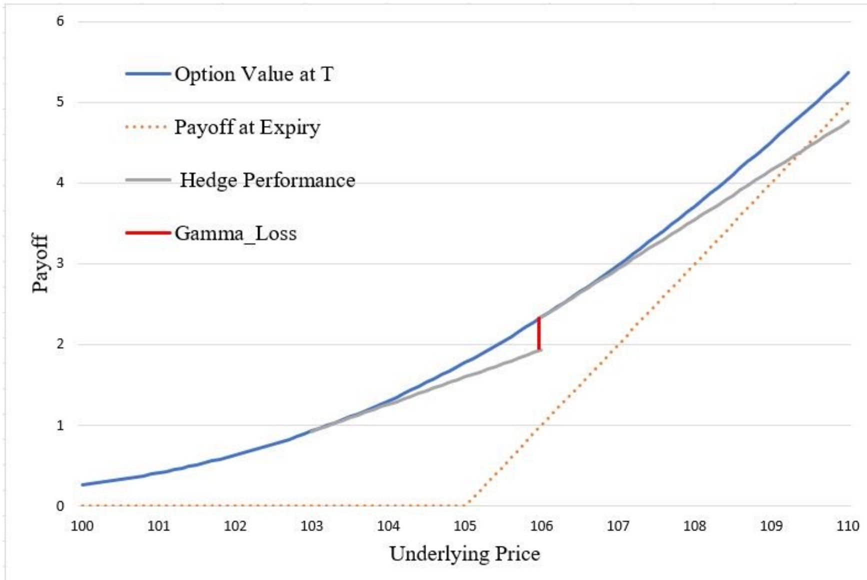
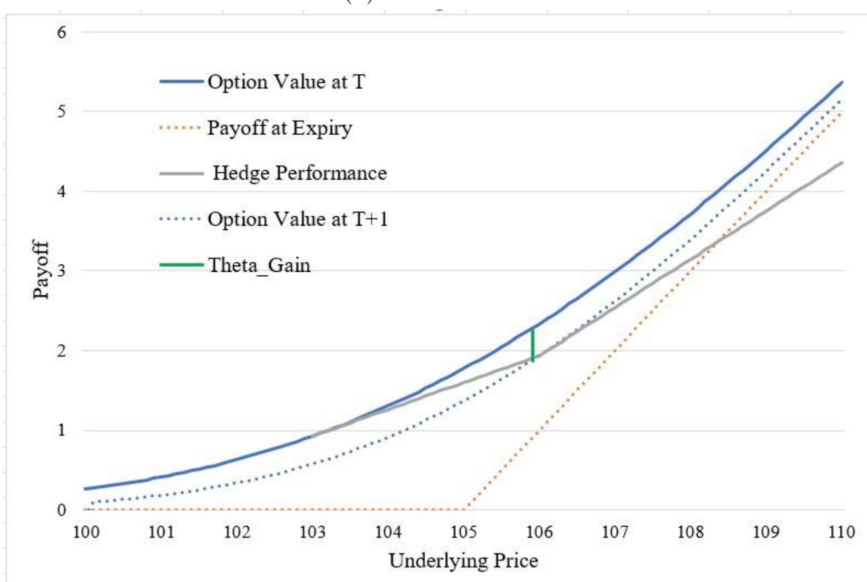


(a) Gamma Loss



(b) Theta Gain

Figure 1: Delta neutral portfolio to replicate a call option position

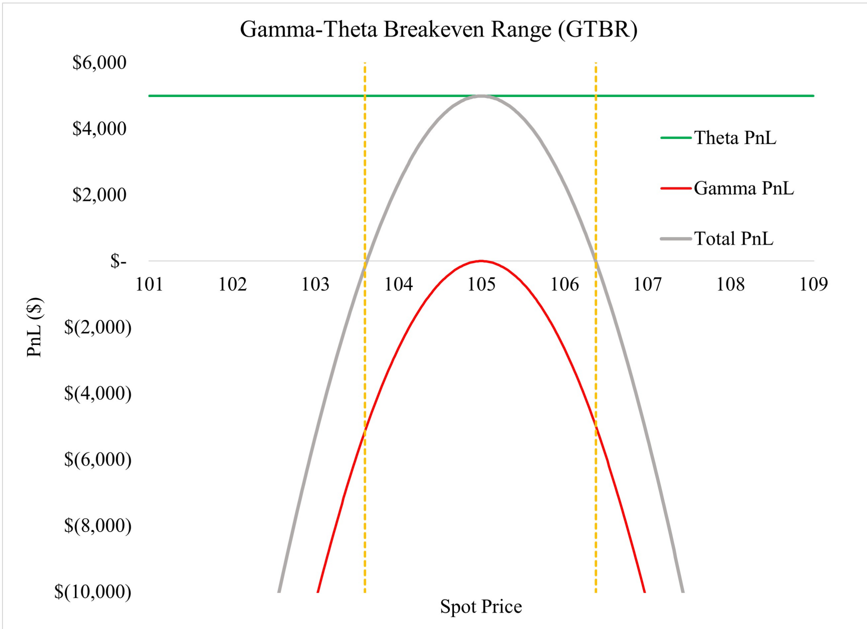
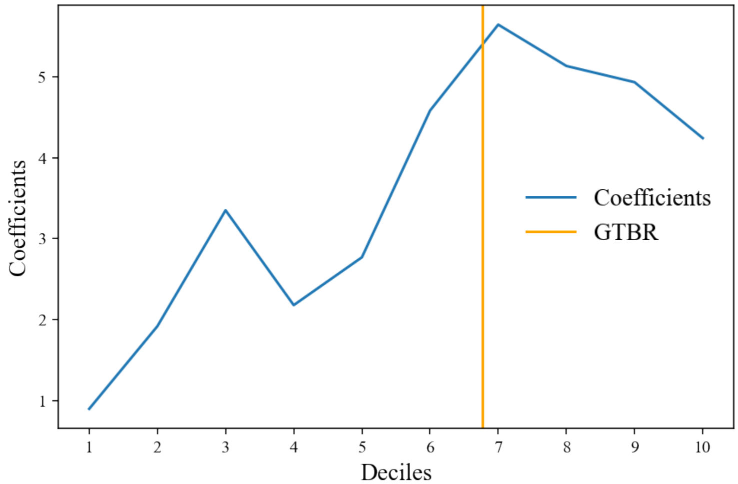
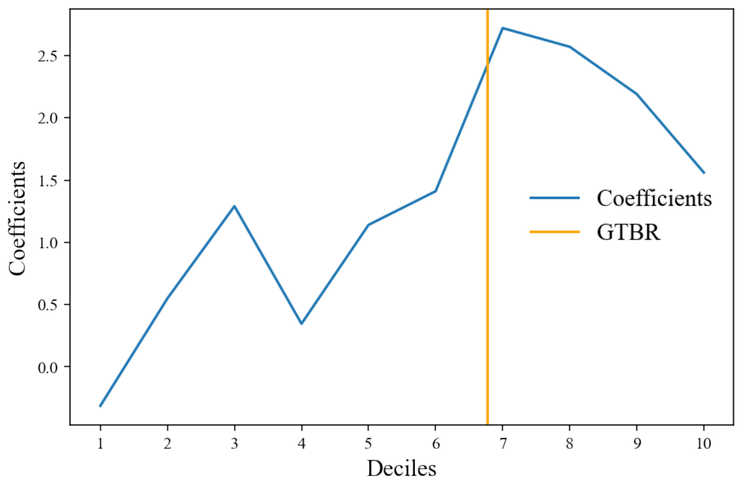


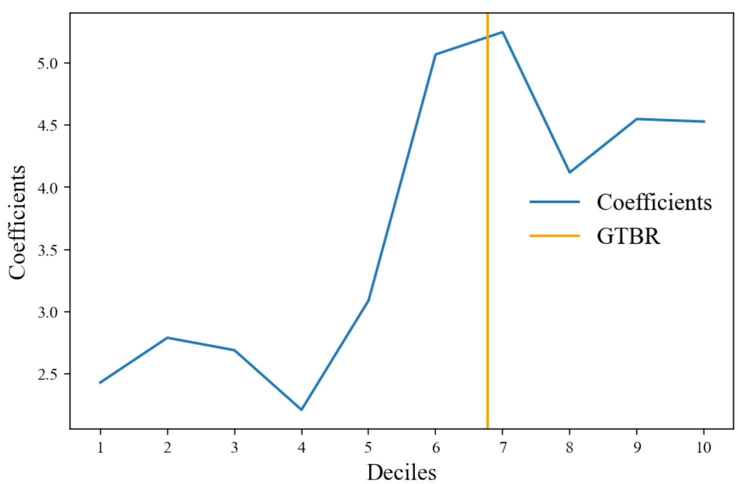
Figure 2: Intraday PnL change by spot price movement
NOTE: MM has a short option leg with its delta hedge leg at the underlying price of 105



(a) By using all data

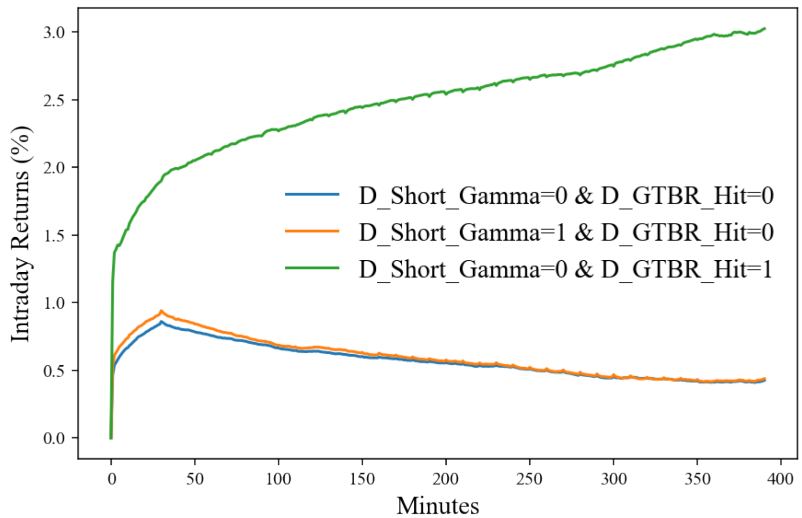


(b) By using data with **positive** return for the first 30 minutes

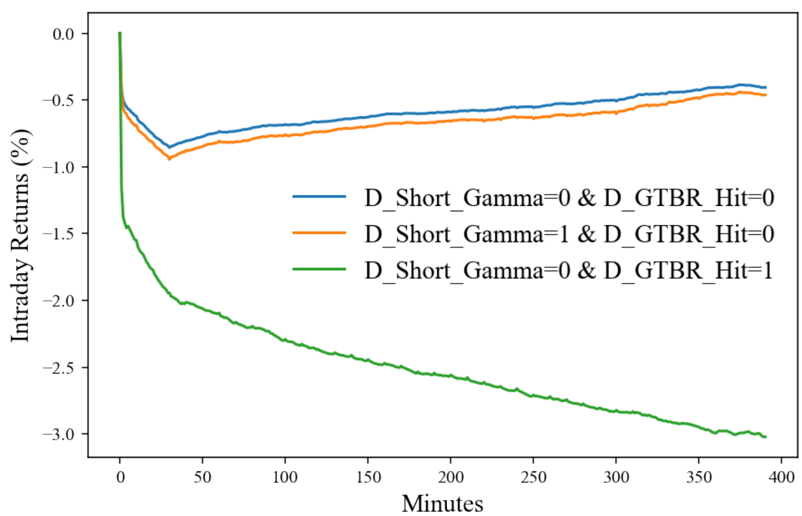


(c) By using data with **negative** return for the first 30 minutes

Figure 3: Momentum coefficient from deciles



(a) The underlying stock price **up** at the first 30 minutes



(b) The underlying stock price **down** at the first 30 minutes

Figure 4: The market intraday momentum depending on hitting GTBR and short gamma exposure

Table 1: An example of a delta-neutral trader's dillemma

At the market close on T-1 , MM has a delta-neutral portfolio by $10 mio short call options and delta-hedged position. The call option has the following specifications: Underlying price: $100, Strike price: $100, Days to expiry: 30 days, Interest rate 3%, Notional amount: $10 millions (mio), Volatility: 22%. This option opens the following Greeks: delta: 0.539, gamma: 0.046, Theta: -0.061. All below cases consider the underlying moves up 1%, 180 minutes (180m) after market opens but MM takes different actions.

Case 1:	Underlying moves up 1% at 180m and down back to flat at 390m MM does nothing						
		Delta$	Gamma$	Gamma PnL	Theta PnL	Trading PnL	Total PnL
T-1 close		0.00k	-461.64k	0.00k	0.00k	0.00k	0.00k
T_180m	+1%	-619.01k	-448.95k	-3.10k	6.11k	0.00k	2.15k
T_390m	**+0%**	0.00k	-461.64k	0.00k	6.11k	0.00k	6.11k

Case 2:	Underlying moves up 1% at 180m and up further to 2% at 390m MM does nothing						
		Delta$	Gamma$	Gamma PnL	Theta PnL	Trading PnL	Total PnL
T-1 close		0.00k	-461.64k	0.00k	0.00k	0.00k	0.00k
T_180m	+1%	-619.01k	-448.95k	-3.10k	6.11k	0.00k	2.15k
T_390m	**+2%**	-1207.93k	-426.16k	-12.08k	6.11k	0.00k	-5.97k

Case 3:	Underlying moves up 1% at 180m and up further to 2% at 390m MM rebalances at 180m						
		Delta$	Gamma$	Gamma PnL	Theta PnL	Trading PnL	Total PnL
T-1 close		0.00k	-461.64k	0.00k	0.00k	0.00k	0.00k
T_180m	+1%	-619.01k	-448.95k	-3.10k	6.11k	0.00k	2.15k
T_390m	**+2%**	-588.91k	-426.16k	-12.08k	6.11k	6.19k	0.22k

Case 4:	Underlying moves up 1% at 180m and up further to 2% at 390m MM rebalances at 180m						
		Delta$	Gamma$	Gamma PnL	Theta PnL	Trading PnL	Total PnL
T-1 close		0.00k	-461.64k	0.00k	0.00k	0.00k	0.00k
T_180m	+1%	-619.01k	-448.95k	-3.10k	6.11k	0.00k	2.15k
T_390m	**+0%**	+619.01k	-461.64k	0.00k	6.11k	-6.19k	-0.08k

Table 2: Regression of the last 30 minutes by the first 30 minutes with the indicator variables from short gamma and hitting GTBR

This table reports the regression of the last 30 minutes by the first 30 minutes with the interactive variables. *D_Short_Gamma* equals 1 if the MM has a short gamma position and 0 otherwise. *D_GTBR_hit* equals 1 if the underlying hit the Gamma-Theta Breakeven Range (GTBR) at 360 minutes after the market opens and 0 otherwise. Newey and West (1986) t-statistics are in parentheses. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, respectively and coefficients are multiplied by 100.

	Dependent: r_{390_360}				
Independent	(1)	(2)	(3)	(4)	(5)
r_{30_0}	1.82***	1.64***	1.22***	1.05***	-1.16***
	(18.06)	(14.82)	(7.93)	(6.49)	(-4.20)
$r_{30\_0} \cdot D\_Short\_Gamma$		0.72***		0.71***	0.56**
		(2.98)		(2.97)	(2.32)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			0.95***	0.96***	1.18***
			(5.01)	(5.00)	(6.07)
$r_{30\_0} \cdot D\_Earning$					-2.41***
					(-5.40)
$r_{30\_0} \cdot ImpliedVol$					3.66***
					(7.84)
$Adj.R^2(\%)$	0.26	0.26	0.27	0.28	0.40
Firm F.E.	Yes	Yes	Yes	Yes	Yes
Observations	342,264	342,264	342,264	342,264	342,185

Table 3: Regression of the last 30 minutes on the first 30 minutes by sorted data

This table reports the regression of the last 30 minutes on the first 30 minutes with the sorted data set. After measuring the hitting GTBR every minute, $Cumul\_Hit\_GTBR_{360}$ is calculated by the cumulative hit number for the first 360 minutes and then categorized by the number. $NormGamma$ is normalized dollar gamma and they are categorized by quintile. $NormGamma^1$ has the strongest short gamma while $NormGamma^5$ has the strongest long gamma. The $Cumul\_Hit\_GTBR$ has been sorted first and then $NormGamma$ are categorized. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, respectively and coefficients are multiplied by 100.

r_{390_360} on r_{30_0}	**(Short Gamma)**				**(Long Gamma)**
	$NormGamma^1$	$NormGamma^2$	$NormGamma^3$	$NormGamma^4$	$NormGamma^5$
$Cumul\_Hit\_GTBR_{360} = 0$	0.23	1.42**	-0.20	-0.29	-1.25**
	(0.40)	(2.52)	(-0.55)	(-0.41)	(-2.73)
$0 < Cumul\_Hit\_GTBR_{360} < 90$	2.25***	3.57***	0.91**	0.23	0.21
	(4.31)	(6.96)	(2.02)	(0.51)	(0.52)
$90 \leq Cumul\_Hit\_GTBR_{360} < 180$	2.16***	3.77***	2.19***	0.61	0.98*
	(4.32)	(5.40)	(3.30)	(0.91)	(1.65)
$180 \leq Cumul\_Hit\_GTBR_{360} < 270$	2.21***	4.51***	2.72***	0.91	0.20
	(3.19)	(6.74)	(4.24)	(1.52)	(0.34)
$270 \leq Cumul\_Hit\_GTBR_{360} < 360$	3.09***	3.70***	1.59***	1.06***	-0.49*
	(8.23)	(9.85)	(4.56)	(3.22)	(-1.59)
$Cumul\_Hit\_GTBR_{360} = 360$	1.04**	3.88***	1.87***	1.13***	-0.03
	(2.10)	(6.99)	(3.96)	(2.71)	(-0.07)

Table 4: Regression of the open interest of MM on the cumulative hit number of GTBR by the direction of the market and previous MMs' gamma imbalance

This table reports the regression of the open interest of MM on the cumulative hit number of GTBR by the direction of the market and previous MMs' gamma imbalance. $Cumul\_Hit\_GTBR_{390}$ is the cumulative hit numer of GTBR for a day ad $MM\_OI_{T,i}$ is the open interest of MM for a day. Newey and West (1986) t-statistics are in parentheses. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, respectively

Independent: $Cumul\_Hit\_GTBR_{390}$	Dependent: Dependent: $MM\_OI_{T,i}$	
	MMs' gamma imbalance	
	Long	**Short**
Underlying moves		
Up	0.27***	-0.13
	(8.94)	(-1.18)
Down	0.12***	0.04
	(3.60)	(0.43)
Firm F.E	Yes	Yes
Observations	266,150	71,453

Table 5: Regression of the last 30 minutes on the first 30 minutes by professional investor's option holdings

This table reports the regression of the last 30 minutes on the first 30 minutes by professional investor's option holdings. $Prof\_Option\_Holding$ = 1 if the active professional investor's option open interest is positive and 0 otherwise. D_Short_Gamma equals 1 if the MM has a short gamma position and 0 otherwise. D_GTBR_hit equals 1 if the underlying hit the Gamma-Theta Breakeven Range (GTBR) at 360 minutes after the market opens and 0 otherwise. Newey and West (1986) t-statistics are in parentheses. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ for the regressions (1) to (6), respectively and coefficients are multiplied by 100. The statistics for difference is Wald statistics following chi-squared distribution.

	Dependent: r_{390_360}								
	$Prof\_Option\_Holding = 0$			$Prof\_Option\_Holding = 1$			$Difference$		
Independent:	(1)	(2)	(3)	(4)	(5)	(6)	(4)-(1)	(5)-(2)	(6)-(3)
r_{30_0}	1.66***	1.42***	-0.92***	1.56***	0.49***	-3.02***	0.23	-0.93***	-2.10***
	(18.99)	(11.75)	(-4.63)	(14.38)	(2.93)	(-10.62)	(0.23)	(8.76)	(12.44)
$r_{30\_0} \cdot D\_Short\_Gamma$	0.83***		0.76***	-0.02		-0.40	-0.84		-1.16**
	(4.92)		(4.51)	(-0.06)		(-1.42)	(2.51)		(4.78)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$		0.76***	0.94***		1.66***	1.98***		0.90**	1.04***
		(4.95)	(6.08)		(7.97)	(9.42)		(5.29)	(6.96)
$r_{30\_0} \cdot D\_Earning$			-2.16***			-3.04***			-0.88
			(-5.59)			(-6.14)			(0.97)
$r_{30\_0} \cdot ImpliedVol$			3.29***			7.59***			4.30***
			(14.05)			(15.79)			(11.87)
FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	241,086	241,086	241,025	101,178	101,178	101,160	342,264	342,264	342,185

Table 6: Regression of the last 30 minutes on the first 30 minutes by the direction of the first 30 minutes

This table reports the regression of the last 30 minutes on the first 30 minutes with the interactive variables. Regressions in Table (a) run with the data where the market rises at the first 30 minutes while regressions in Table (b) does with the data where the market moves down at the first 30 minutes. D_Short_Gamma equals 1 if the MM has a short gamma position and 0 otherwise. D_GTBR_hit equals 1 if the underlying hit the Gamma-Theta Breakeven Range (GTBR) at 360 minutes after the market opens and 0 otherwise. Newey and West (1986) t-statistics are in parentheses. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, respectively and coefficients are multiplied by 100.

(a) The underlying stock price **up** at the first 30 minutes

	Dependent: r_{390_360}				
Independent	(1)	(2)	(3)	(4)	(5)
r_{30_0}	3.98***	3.81***	3.91***	3.75***	2.82***
	(20.45)	(18.68)	(13.08)	(12.02)	(5.43)
$r_{30\_0} \cdot D\_Short\_Gamma$		0.61*		0.61*	0.60*
		(1.83)		(1.83)	(1.80)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			0.09	0.08	0.40
			(0.31)	(0.29)	(1.35)
$r_{30\_0} \cdot D\_Earning$					-4.20***
					(-6.78)
$r_{30\_0} \cdot ImpliedVol$					1.59***
					(2.12)
Firm F.E	Yes	Yes	Yes	Yes	Yes
Observations	170,868	170,868	170,868	170,868	170,847

(b) The underlying stock price **down** at the first 30 minutes

	Dependent: r_{390_360}				
Independent	(1)	(2)	(3)	(4)	(5)
r_{30_0}	1.02***	0.78**	-0.03	-0.28	-5.16*
	(5.22)	(3.78)	(-0.09)	(-0.88)	(-10.65)
$r_{30\_0} \cdot D\_Short\_Gamma$		1.35***		0.95***	0.74***
		(4.55)		(2.86)	(2.23)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			1.35***	1.37***	1.65***
			(4.55)	(4.57)	(5.51)
$r_{30\_0} \cdot Earning$					-0.56
					(-0.86)
$r_{30\_0} \cdot ImpliedVol$					6.77***
					(10.41)
Firm F.E	Yes	Yes	Yes	Yes	Yes
Observations	168,256	168,256	168,256	168,256	168,298

Table 7: Regression of the last 30 minutes on the first 30 minutes with Gamma positions from calls, puts, upside strikes, and downside strikes by the direction of the first 30 minutes

This table reports the regression of the last 30 minutes on the first 30 minutes with Gamma positions from calls, puts, upside strikes, and downside strikes by the direction of the first 30 minutes. Regressions in Table (a) run with all data. Regressions in Table (b) run with the data where the market rises at the first 30 minutes while regressions in Table (c) do with the data where the market moves down at the first 30 minutes. *D_Short_Gamma_Calls* (*D_Short_Gamma_Puts*) equals 1 if the MM has a short gamma position from call (put) options and 0 otherwise. *D_Short_Gamma_Upsides* (*D_Short_Gamma_Downsides*) equals 1 if the MM has a short gamma position from upside strike (downside strike) options and 0 otherwise. *D_GTBR_hit* equals 1 if the underlying hit the Gamma-Theta Breakeven Range (GTBR) at 360 minutes after the market opens and 0 otherwise. Newey and West (1986) t-statistics are in parentheses. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, respectively and coefficients are multiplied by 100.

	(a) All data									
					r_390_360					
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
r_{30_0}	1.82***	1.65***	1.62***	1.85***	1.62***	1.22***	1.06***	1.03***	1.25***	1.02***
	(18.06)	(15.01)	(15.01)	(17.18)	(14.62)	(7.93)	(6.57)	(6.34)	(7.90)	(6.33)
$r_{30\_0} \cdot D\_Short\_Gamma\_Calls$		0.71***		0.70***						
		(2.86)		(2.85)						
$r_{30\_0} \cdot D\_Short\_Gamma\_Puts$					0.82***	0.81***				
					(3.47)	(3.42)				
$r_{30\_0} \cdot D\_Short\_Gamma\_Upsides$							-0.29	-0.32		
							(-1.04)	(-1.15)		
$r_{30\_0} \cdot D\_Short\_Gamma\_Downsides$									0.87***	0.87***
									(3.54)	(3.54)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			0.96***	0.96***		0.96***		0.97***		0.96***
			(5.01)	(5.01)		(5.00)		(5.03)		(5.01)
Observations	342,264	342,264	342,264	342,264	342,264	342,264	342,264	342,264	342,264	342,264

(b) The underlying **up** at the first 30 minutes

Variable	r_390_360 (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
r_{30_0}	3.98***	3.85***	3.76***	3.98***	3.83***	3.91***	3.78***	3.70***	3.91**	3.77***
	(20.45)	(18.89)	(18.23)	(19.83)	(18.76)	(13.08)	(12.43)	(12.08)	(12.95)	(12.39)
$r_{30\_0} \cdot D\_Short\_Gamma\_Calls$		0.51		0.51						
		(1.51)		(1.50)						
$r_{30\_0} \cdot D\_Short\_Gamma\_Puts$					0.83**	0.82**				
					(2.55)	(2.55)				
$r_{30\_0} \cdot D\_Short\_Gamma\_Upsides$							0.01	0.01		
							(0.04)	(0.03)		
$r_{30\_0} \cdot D\_Short\_Gamma\_Downsides$									0.57	0.57
									(1.70)	(1.70)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			0.08	0.08		0.09		0.08		0.08
			(0.29)	(0.27)		(0.31)		(0.29)		(0.29)
Observations	170,868	170,868	170,868	170,868	170,868	170,868	170,868	170,868	170,868	170,868

(c) The underlying **down** at the first 30 minutes

Variable	r_390_360 (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
r_{30_0}	1.02***	0.75***	0.79***	1.04***	0.73***	-0.03	-0.31	-0.26	-0.01	-0.34
	(5.22)	(3.65)	(3.83)	(5.19)	(3.57)	(-0.09)	(-0.98)	(-0.82)	(-0.03)	(-1.09)
$r_{30\_0} \cdot D\_Short\_Gamma\_Calls$		1.13***		1.13***						
		(3.29)		(3.32)						
$r_{30\_0} \cdot D\_Short\_Gamma\_Puts$					0.85***	0.86***				
					(2.61)	(2.64)				
$r_{30\_0} \cdot D\_Short\_Gamma\_Upsides$							-0.23	-0.32		
							(-0.57)	(-0.78)		
$r_{30\_0} \cdot D\_Short\_Gamma\_Downsides$									1.23***	1.27***
									(3.67)	(3.77)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			1.35***	1.37***		1.36***		1.37***		1.38***
			(4.55)	(4.57)		(4.56)		(4.57)		(4.63)
Observations	168,256	168,256	168,256	168,256	168,256	168,256	168,256	168,256	168,256	168,256

Table 8: Regression of the last 30 minutes on the first 30 minutes with the indicator variables from short gamma and hitting GTBR with the subset

This table reports the regression of the last 30 minutes by the first 30 minutes with the interactive variables. D_Short_Gamma equals 1 if the MM has a short gamma position and 0 otherwise. D_GTBR_hit equals 1 if the underlying hit the Gamma-Theta Breakeven Range (GTBR) at 360 minutes after the market opens and 0 otherwise. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, respectively and coefficients are multiplied by 100. All regressions use the firm-fixed effect.

(a) With the subset of **the expiry week**

	Dependent: r_{390_360}				
Independent	(1)	(2)	(3)	(4)	(5)
r_{30_0}	2.17***	1.88***	1.18***	0.89***	-4.28***
	(10.60)	(8.19)	(3.84)	(2.76)	(-7.66)
$r_{30\_0} \cdot D\_Short\_Gamma$		1.22**		1.22**	0.94*
		(2.47)		(2.47)	(1.90)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			1.65***	1.65***	1.91***
			(4.25)	(4.25)	(4.87)
$r_{30\_0} \cdot D\_Earning$					-1.34
					(-1.38)
$r_{30\_0} \cdot ImpliedVol$					8.46***
					(8.75)
$Adj.R^2(\%)$	0.34	0.36	0.38	0.40	0.91
Firm F.E	Yes	Yes	Yes	Yes	Yes
Observations	79,281	79,281	79,281	79,281	79,261

(b) With the subset of **the non-expiry week**

	Dependent: r_{390_360}				
Independent	(1)	(2)	(3)	(4)	(5)
r_{30_0}	1.74***	1.60***	1.24***	1.10***	-0.31*
	(15.30)	(12.77)	(7.00)	(5.93)	(-1.00)
$r_{30\_0} \cdot D\_Short\_Gamma$		0.57**		0.57**	0.46*
		(2.10)		(2.09)	(1.69)
$r_{30\_0} \cdot D\_GTBR\_hit_{360}$			0.79***	0.79***	0.99***
			(3.61)	(3.60)	(4.45)
$r_{30\_0} \cdot D\_Earning$					-2.72***
					(-5.43)
$r_{30\_0} \cdot ImpliedVol$					2.37***
					(4.56)
$Adj.R^2(\%)$	0.24	0.24	0.25	0.25	0.33
Firm F.E	Yes	Yes	Yes	Yes	Yes
Observations	262,983	262,983	262,983	262,983	262,924

Table 9: Summary statistics of the R^2 and OOSR2 from the regressions for each underlying

This table represents the summary statistics of the R^2 and OOSR2 from the regression by each underlying. The data are first grouped by underlying, and then at each underlying level the last 30 minute return is regressed by the first 30 minute return. The column (1), (2), (3), and (4) shows the different regressions for r_{390_360}. The column (1) is the regression by only r_{30_0}, the regression (2) adds *D_Short_Gamma* interaction to the regression (1), the regression (3) adds *D_GTBR_hit* interaction to the regression (1), and the regression (4) includes all indicators.

	R^2				OOSR2			
Stat	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Mean	0.87	1.34	1.18	1.82	1.34	1.54	1.57	1.78
StdDev	1.52	2.75	1.79	3.14	7.24	9.80	7.87	10.06
Min	0.00	0.00	0.00	0.00	-1.21	-1.68	-1.31	-1.71
$25^{th} Percentile$	0.10	0.20	0.20	0.50	0.45	0.62	0.59	0.77
Median	0.30	0.60	0.50	1.00	0.90	1.20	1.09	1.40
$75^{th} Percentile$	0.90	1.40	1.30	2.00	1.91	2.34	2.31	2.63
Max	9.90	35.10	12.10	39.10	23.26	27.49	26.82	28.72

Appendices

A1. Simplifying daily PnL attribution

From Carr and Wu (2020), the instantaneous PnL of the option position is,

$$
\begin{aligned}
dPnL =& Theta * dT + Delta * dS + Vega * dI \\
&+ \frac{1}{2}Gamma(dS)^2 + \frac{1}{2}Volga(dI)^2 + \frac{1}{2}Vanna(dS)(dI) + J_T
\end{aligned}
$$

where dS, dI, and J_T represent an underlying price change, an implied volatility change, and a PnL change by higher orders. MMs' delta-neutral portfolio begins a day with delta-neutral and rebalances its delta by the end of the day. Therefore, in the delta-hedged portfolio, the delta PnL of the option can be deleted. Also, assuming that there's no significant change in higher order PnL during the day, a daily PnL attribution is

$$
Daily\ PnL = \frac{Theta}{365} + \frac{1}{2}Gamma(\Delta S)^2 + Trading\ PnL
$$

Vega, Volga, and Vanna PnL is negligible compared to gamma PnL in the scope of this study because gamma exposure is significant at relatively shorter maturity. In short maturity, vega volga, and vanna are relatively small and implied volatility during the day does not change significantly very frequently.

A2. The optimal hedge trigger point for a trader's perspective

This equation can be rewritten as below.

$$
\begin{aligned}
E_t[PnL_T] &= E_t[50\Gamma r_{T-t}^2 + 50\Gamma r_t^2 + H\{(r_{T-t} - 100k\Gamma r_t)(-100\Gamma r_t) - |100\Gamma r_t \cdot tc|\}|r_t] + \theta_1 \\
&= E_t[50\Gamma r_{T-t}^2|r_t] + 50\Gamma r_t^2 + E_t[H\{(r_{T-t} - 100k\Gamma r_t)(-100\Gamma r_t) - |100\Gamma r_t \cdot tc|\}|r_t] + \theta_1
\end{aligned}
$$

Let $r_{T-t} = \mu(T-t) + \sigma(W(T) - W(t)) + Hk(-100\Gamma r_t)$ where μ is a hedger's belief for average return, $W(t)$ is a brownian. Then,

$$
\begin{aligned}
=&50\Gamma\mu^2(T-t)^2 + 50\Gamma\sigma^2(T-t) + H^2k^2 100^2\Gamma^2 r_t^2 - 100^2\Gamma^2\mu(T-t)Hkr_t + 50\Gamma r_t^2 \\
&+ H\mu(T-t)(-100\Gamma r_t) - |100\Gamma r_t \cdot tc| + \theta_1
\end{aligned}
$$

Assume that MM tries to find the rebalancing timing ($H = 1$), then

$$\begin{aligned}=&50\Gamma\mu^2(T-t)^2 + 50\Gamma\sigma^2(T-t) + k^2 100^2\Gamma^2 r_t^2 - 100^2\Gamma^2\mu(T-t)kr_t + 50\Gamma r_t^2 \\ &+ \mu(T-t)(-100\Gamma r_t) - |100\Gamma r_t \cdot tc| + \theta_1\end{aligned} \tag{5}$$

A delta-neutral trader maximizes the expected PnL,

$$max\ E_t[PnL_T]$$

F.O.C for $E_t[PnL_T]$ by r_t, r_t^* is

$$2k^2 100^2\Gamma^2 r_t^* - 100^2\Gamma^2\mu(T-t)k + 100\Gamma r_t^* + \mu(T-t)(-100\Gamma) - |100\Gamma \cdot tc| = 0$$

$$r_t^* = \frac{\mu(T-t)(1+100\Gamma k) + tc'}{(1+2\cdot 100^2 k^2\Gamma^2)} \tag{6}$$

where $tc' = tc$ if $\Gamma >= 0$, and $tc' = -tc$ if $\Gamma < 0$.

r_t^* is the gamma hedge triggering level of the hedge trader or MM at t. This level would vary depending on the remaining time for the day, return drift, the impact cost, and the transaction cost.

A3. Simplifying the GTBR

From equation (1) in Section 2.3.1, GTBR is derived as below.

$$GTBR = \pm\sqrt{-\frac{\theta}{365\cdot 50\Gamma}}$$

and from Black-Scholes greek, assuming zero dividend, theta is calculated to

$$\theta_{Call} = -\frac{SN'(d_1)\sigma_{imp}}{2\sqrt{T-t}} - rKe^{-r(T-t)}N(d_2)$$
$$\theta_{Put} = -\frac{SN'(d_1)\sigma_{imp}}{2\sqrt{T-t}} + rKe^{-r(T-t)}N(-d_2)$$

where σ_{imp} is implied volatility of an option. Only when the option has deep ITM moneyness do the second terms in the above equations have meaningful value. However, because deep ITM options almost never have any gamma exposure, they have no impact on a hedge trader's decision.

As a result, Black-Scholes theta as a gamma risk buffer is approximately

$$\theta \approx -\frac{SN'(d_1)\sigma_{imp}}{2\sqrt{T-t}} \tag{7}$$

Also, the dollar gamma, Γ is

$$\Gamma = \frac{\gamma S^2}{100} = \frac{N'(d_1)}{100 \cdot S\sigma\sqrt{T-t}}S^2 = \frac{SN'(d_1)}{100\sigma\sqrt{T-t}} \tag{8}$$

By plugging equation (7) and (8) into the equation (1),

$$GTBR \approx \pm\sqrt{-\frac{\theta}{365 \cdot 50\Gamma}} = \pm\sqrt{-\frac{\frac{SN'(d_1)\sigma}{2\sqrt{T-t}}}{365 \cdot 50 \cdot \frac{SN'(d_1)}{100\sigma_{imp}\sqrt{T-t}}}} = \pm\sqrt{\frac{\sigma_{imp}^2}{365}} = \pm\frac{\sigma_{imp}}{\sqrt{365}} \tag{9}$$

B1. Descriptive Statistics

Table B1: Descriptive Statistics: Raw data

(a) Summary statistics

Variable	Mean	Standard Deviation	Min	$25^{th} Percentile$	Median	$75^{th} Percentile$	Max
r_{30_0}	0.0000406	0.0168	-0.0543	-0.00792	0	0.00813	0.0549
r_{390_360}	0.0000757	0.0059	-0.0211	-0.00245	0	0.00249	0.0228
$Cumul\_GTBR\_Hit_{360}$	91.29	124.9	0	0	10	175	360
Gamma_Size	6,098	44,894	-3,501,893	68	1,587	7077	837,537

(b) Correlation among dependent variables

Correlation	r_{30_0}	D_Short_Gamma	$D\_GTBR\_Hit_{360}$	$Cumul\_GTBR\_Hit_{360}$	r_{30_0} * D_Short_Gamma	r_{30_0} * $D\_GTBR\_Hit_{360}$
r_{30_0}	1					
D_Short_Gamma	0.0008	1				
$D\_GTBR\_Hit_{360}$	0.0007	0.0061	1			
$Cumul\_GTBR\_Hit_{360}$	-0.0082	0.0048	0.7634	1		
$r_{30\_0} \cdot D\_Short\_Gamma$	0.4946	0.0033	0.0041	-0.0035	1	
$r_{30\_0} \cdot D\_GTBR\_Hit_{360}$	0.7885	0.003	0.0021	-0.003	0.3918	1

(c) Frequency of the binary variable

		$D\_GTBR\_Hit_{360}$	
		0	1
D_Short_Gamma	0	183,168	86,721
	1	48,610	23,757

Table B2: Descriptive Statistics: r_{390_360} for sorted data

r_{390_360}		$NormGamma^1$	$NormGamma^2$	$NormGamma^3$	$NormGamma^4$	$NormGamma^5$
$Cumul\_Hit\_GTBR$ (=0)	Mean	0.000069	0.000031	0.000091	0.000008	0.000049
	Std. dev.	0.006079	0.007681	0.005502	0.004420	0.003519
	Min	-0.102644	-0.14852	-0.058900	-0.052167	-0.0399991
	Max	0.132371	0.14634	0.063478	0.060193	0.104304
	Obs	28,681	28,680	28,680	28,680	28,680
$Cumul\_Hit\_GTBR$ (0 - 90)	Mean	0.000086	0.000491	0.000195	0.000141	-0.00003
	Std. dev.	0.009189	0.011207	0.008071	0.006246	0.00453
	Min	-0.132743	-0.089247	-0.097598	-0.063326	-0.09288
	Max	0.145581	0.132691	0.093366	0.110095	0.07224
	Obs	16,785	16,785	16,784	16,785	16,784
$Cumul\_Hit\_GTBR$ (90 - 180)	Mean	0.000211	-0.000027	0.000293	0.000172	-0.000042
	Std. dev.	0.0096736	0.011129	0.008037	0.006348	0.004539
	Min	-0.159223	-0.080498	-0.066062	-0.05810	-0.048345
	Max	0.096310	0.204941	0.111568	0.085424	0.061966
	Obs	6,228	6,227	6,227	6,227	6,227
$Cumul\_Hit\_GTBR$ (180 - 270)	Mean	0.000068	0.00016	0.000073	-0.000010	-0.00002
	Std. dev.	0.0008996	0.011315	0.006759	0.006584	0.004588
	Min	-0.071074	-0.14090	-0.021053	-0.17741	-0.053929
	Max	0.116999	0.189873	0.022757	0.051985	0.045179
	Obs	5,918	5,917	5,918	5,917	5,917
$Cumul\_Hit\_GTBR$ (270 - 360)	Mean	0.000104	-0.0001	-0.000023	0.000001	-0.000031
	Std. dev.	0.010278	0.011616	0.008284	0.005905	0.004652
	Min	-0.089091	-0.127197	-0.088250	-0.044040	-0.048824
	Max	0.451178	0.151724	0.130171	0.073844	0.051443
	Obs	8,714	8,714	8,714	8,714	8,714
$Cumul\_Hit\_GTBR$ (=360)	Mean	0.000285	0.0007611	0.000406	0.000376	0.000076
	Std. dev.	0.008875	0.012107	0.008880	0.006843	0.004680
	Min	-0.047458	-0.071090	-0.1358	-0.034378	-0.032619
	Max	0.084349	0.085691	0.054945	0.046577	0.029706
	Obs	2,128	2,128	2,128	2,128	2,127

Table B3: Descriptive Statistics: r_{30_0} for sorted data

r_{30_0}		$NormGamma^1$	$NormGamma^2$	$NormGamma^3$	$NormGamma^4$	$NormGamma^5$
$Cumul\_Hit\_GTBR$ (=0)	Mean	0.000154	0.000191	0.000048	0.000108	0.00011
	Std. dev.	0.00878	0.010323	0.008603	0.007373	0.006145
	Min	-0.062036	-0.086926	-0.08483	-0.065057	-0.043315
	Max	0.073018	0.083793	0.06175	0.048946	0.05006
	Obs	28,681	28,680	28,680	28,680	28,680
$Cumul\_Hit\_GTBR$ (0 - 90)	Mean	0.000182	0.000414	0.000106	0.000029	0.000132
	Std. dev.	0.015505	0.017969	0.015638	0.013389	0.010801
	Min	-0.092147	-0.164706	-0.097135	-0.078518	-0.085701
	Max	0.132202	0.166128	0.129191	0.093663	0.05749
	Obs	16,785	16,785	16,784	16,785	16,784
$Cumul\_Hit\_GTBR$ (90 - 180)	Mean	0.000103	0.000394	-0.000276	-0.00029	-0.000138
	Std. dev.	0.018389	0.020473	0.018165	0.01547	0.012727
	Min	-0.16285	-0.156803	-0.119932	-0.083798	-0.069178
	Max	0.190086	0.19790	0.126795	0.124507	0.079713
	Obs	6,228	6,227	6,227	6,227	6,227
$Cumul\_Hit\_GTBR$ (180 - 270)	Mean	-0.000472	-0.0009	-0.000423	0.000029	0.000072
	Std. dev.	0.019625	0.021898	0.019162	0.016267	0.013378
	Min	-0.115879	-0.17013	-0.170103	-0.100671	-0.079951
	Max	0.138494	0.230159	0.230159	0.112181	0.077892
	Obs	5,918	5,917	5,918	5,917	5,917
$Cumul\_Hit\_GTBR$ (270 - 360)	Mean	-0.000316	-0.000485	-0.000313	0.0006	0.000893
	Std. dev.	0.028128	0.031434	0.028048	0.024551	0.020291
	Min	-0.664048	-0.548387	-0.185007	-0.502709	-0.499252
	Max	0.206940	0.472279	0.199802	0.130492	0.131375
	Obs	8,714	8,714	8,714	8,714	8,714
$Cumul\_Hit\_GTBR$ (=360)	Mean	0.000573	-0.000156	-0.002476	-0.001387	-0.001286
	Std. dev.	0.041613	0.043701	0.042348	0.040192	0.034732
	Min	-0.899917	-0.6305725	-0.746632	-0.670929	-0.895287
	Max	17.2688	4.012389	4.0888	0.270812	0.24955
	Obs	2,128	2,128	2,128	2,128	2,127

C1. Never broken GTBR for a whole day or broken GTBR for a whole day

Unlike section 4.2, which examined the cumulative GTBR effect for 360 minutes, this appendix section investigates whether market intraday momentum exists even when the underlying never reaches the GTBR and when the underlying market opens and stays out of GTBR for the entire day. The result is shown in Table C4. The first row contains cases in which the underlying never moves out of the GTBR. According to the findings, there is no market intraday momentum but significant market 'reverse' regardless of the gamma size and sign across columns. This implies that when the underlying remains and moves within GTBR, the mean reversion trader has a stronger impact on the market than the trend follower, including the short gamma trader. Besides that, when the MM has a long gamma, the market's intraday reversal is stronger. The last row, which contains cases in which the underlying open and remains out of GTBR for the entire day, yields a similar result to the previous section. With MMs' strong short gamma position, they still have some significant intraday trends, but the overall momentum coefficient is lower than in the normal case (breaking GTBR sometimes during the day). This implies that MMs' delta hedge from short gamma exposure spreads throughout the day because the MMs' position begins with a loss and their hedge activity focus on minimizing their hedge impact. Long gamma exposure, on the other hand, works by reducing the intraday trend without changing its direction to 'reverse.' To put it another way, their delta hedge from long gamma exposure would not push the underlying return into GTBR. The MM starts by making money over theta cost and does not want to hurt the trend too much, so they have a strong incentive to leave the underlying stays out of the GTBR while they hedge. As a result, their intraday coefficient does not experience a significant 'reverse' change. This result confirms again that the market intraday impact from the option hedging demand is not only a function of the short gamma position of them, but also the one with a clear trigger point.

Table C4: Never broken GTBR for wholeday or broken GTBR for wholeday

This table reports the regression of the last 30 minutes on the first 30 minutes with the sorted data set. After measuring the hitting GTBR every minute, $Cumul\_Hit\_GTBR_{390}$ is calculated by the cumulative hit number for the whole day and then categorized by the number. NormGamma is normalized dollar gamma and they are categorized by quintile. $NormGamma^1$ has the strongest short gamma while $NormGamma^5$ has the strongest long gamma. The Cumul_Hit_GTBR has been sorted first and then $NormGamma$ are categorized. *** is $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, respectively and coefficients are multiplied by 100.

r_{390_360} on r_{30_0}	**(Short Gamma)**				**(Long Gamma)**
	$NormGamma^1$	$NormGamma^2$	$NormGamma^3$	$NormGamma^4$	$NormGamma^5$
$Cumul\_Hit\_GTBR_{390} = 0$	-0.911***	-0.178	-1.53***	-1.13***	-2.44***
	(-2.628)	(-0.510)	(-4.514)	(-3.469)	(-7.712)
$< 0 Cumul\_Hit\_GTBR_{390} < 390$	2.58***	3.88***	1.68***	0.858***	0.0614
	(13.87)	(20.37)	(9.495)	(5.111)	(0.384)
$Cumul\_Hit\_GTBR_{390} = 390$	1.32***	3.68***	1.85***	1.57***	0.0988
	(3.505)	(8.205)	(5.001)	(4.450)	(0.344)