
MID-DAY VOLATILITY

SPIKES IN U.S. FUTURES

MARKETS

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Recent work offers mixed results regarding the nature of intraday volatility patterns in futures markets and, specifically, the existence of spikes in futures return volatility during the middle of the U.S. trading day (Crain & Lee, 1995; Kawaller, Koch, & Peterson, 1994). This note analyzes time and sales data on two markets—Eurodollar futures and deutsche mark futures—to investigate the existence of such spikes, and to examine the nature of changes in intraday volatility patterns over time. © 1999 John Wiley & Sons, Inc. *Jrl Fut Mark* 19: 195–216, 1999

INTRODUCTION

The availability of intraday price data has allowed for analysis of market volatility within a much shorter time frame than had previously been

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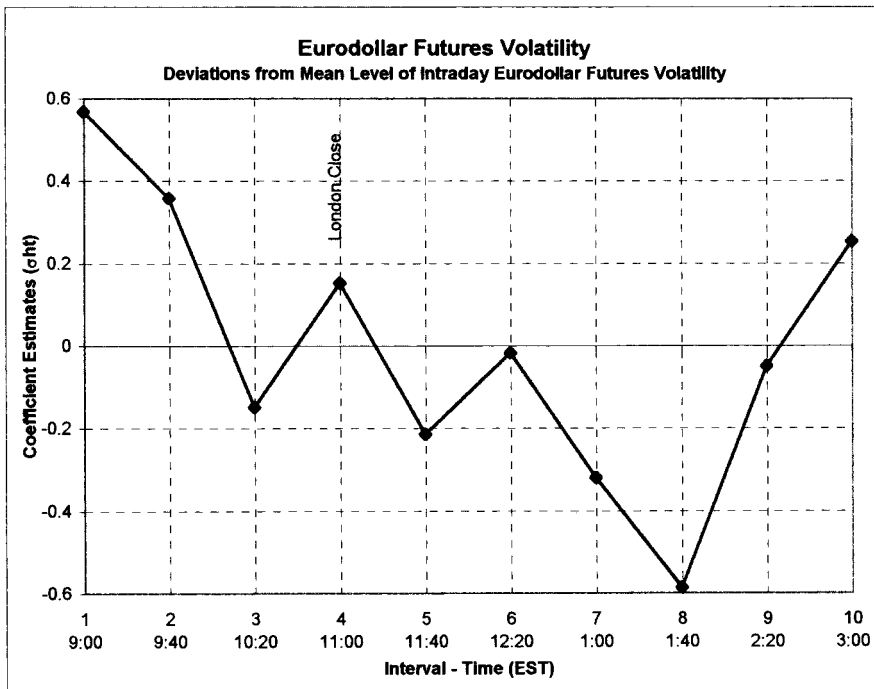
permitted. Jordan et al. (1988) first documented nonconstant intraday volatility patterns in connection with soybean futures markets. Since then, many authors have found similar evidence in a host of other futures markets (Daigler, 1997; Eckman, 1992; Ferguson et al., 1993; Kawaller et al., 1990, 1994; Lee & Linn, 1994; Webb & Smith, 1994). Common to all these studies is the finding that market openings and closings have profound effects on market behavior, reflected by relatively higher volatility at both ends of the typical trading day.¹ One strand of the literature further observes that some spot and futures markets experience spikes in the typical U-shaped intraday volatility pattern at certain times during the middle of the trading day, when related markets are opened or closed.²

This article focuses on two recent papers, by Crain and Lee (1995; henceforth C&L) and by Kawaller, Koch, and Peterson (1994; henceforth KK&P). The two articles document seemingly divergent results regarding the existence of midday volatility spikes in Eurodollar and deutsche mark futures markets.³ As an aid to the reader, the intraday volatility patterns documented in these two studies are distilled and recharted in Figures

¹Several studies document significantly greater volatility at the open and close of trading in NYSE stocks (see Amihud & Mendelson, 1987; Stoll & Whaley, 1990; and Wood, McInish, & Ord, 1985). Daigler (1997) provides a comprehensive discussion of the theoretical and empirical issues raised in the related literature involving futures markets.

²Ferguson et al. (1993) found that the closure of the European spot market affects volatility in foreign exchange futures. Harvey and Huang (1991) also examined foreign exchange futures markets and found that home country business hours have an impact on volatility. In addition, the authors suggested intraday volatility patterns change when European banks close. Hsieh and Kleidon (1994) explored how market closings and openings in New York and London affect intraday volatility patterns in foreign exchange trading. Kawaller et al. (1994) documented midday volatility spikes in Eurodollar and deutsche mark futures markets in the U.S., suggesting this phenomenon may be related to the close of trading in London. Webb and Smith (1994) provided evidence of midday aberrations in volatility in Eurodollar futures markets that are similar to those documented in Kawaller et al. (1994), but which are not coincident with London's market close. King and Wadhwani (1990) set forth a contagion model, presenting how trading in a "primary" market may affect the volatility in other markets as traders observe the primary market's movements for information about their own market's price behavior. The authors predicted a drop in volatility following the close of a primary market. Daigler (1997) and others have documented a tendency for stock index futures volatility to decline in U.S. markets following the close of trading in the underlying stocks. Kleidon and Werner (1996) investigated the behavior of U.K. stocks that are cross-listed in New York, and found the open of the New York market to be associated with high volatility in New York for these stocks—but found no related spike in London volatility at this time.

³Both studies relied on Granger (1969) tests to assess temporal relationships. KK&P tested the lead/lag relationship between historical volatilities in futures returns and implied volatilities of respective futures options, focusing their attention on markets relating to the S&P 500 index, Eurodollars, deutsche marks, and cattle markets during the fourth quarter of 1988. C&L, on the other hand, measured the lead/lag relationship between volatility in spot and futures markets for Eurodollars and deutsche marks over a longer and later sample period, from September 1990 through June 1993. In addition, the primary focus of C&L was on the question of whether volatility patterns differed on days when major macroeconomic news announcements occurred. As part of their respective studies, both articles overlap with discussions of the intraday volatility patterns in Eurodollar and deutsche mark futures.



Coefficients of intraday dummies reflect intraday patterns in historical (σ_{ht}) and implied (σ_{it}) volatility of eurodollar futures. Each intraday interval represents approximately forty minutes of trading activity. The time reported is the ending time of the interval. Thus, interval 1 represents trading activity from 8:20 a.m. - 9:00 a.m., and so forth. Coefficients are estimated using ordinary least squares regression of each volatility measure on a time trend and ten dummy variables representing the ten intraday intervals. Results are presented as deviations from the mean level of intraday volatility. Negative coefficients represent volatility measures for intraday intervals that are below the mean volatility across all intraday intervals.

Interval:	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>
Coefficients (σ_{ht}):	.569	.358	-.148	.153	-.214	-.017	-.319	-.586	-.049	.253
Coefficients (σ_{it}):	.004	-.002	-.002	.002	-.003	.000	-.004	-.002	-.001	.009

Source: Kawaller, Koch and Peterson (1994)

FIGURE 1

1–4. Little information is provided by either KK&P or C&L regarding the statistical significance of individual coefficients in their intraday volatility patterns. Still, several features of these patterns stand out in Figures 1–4. For example, both studies corroborate the existence of higher volatility associated with market openings. Subsequent volatility patterns shown by the two studies, however, appear to be at odds. For Eurodollars, KK&P

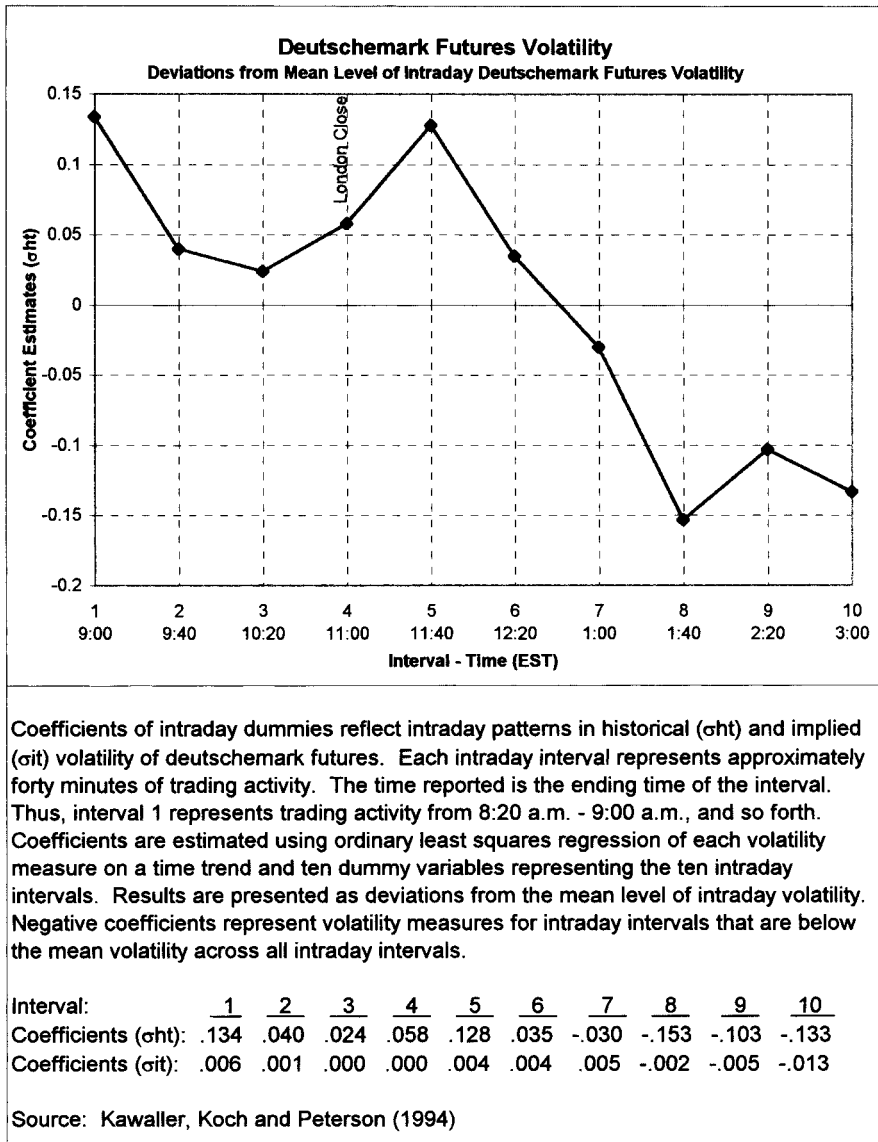
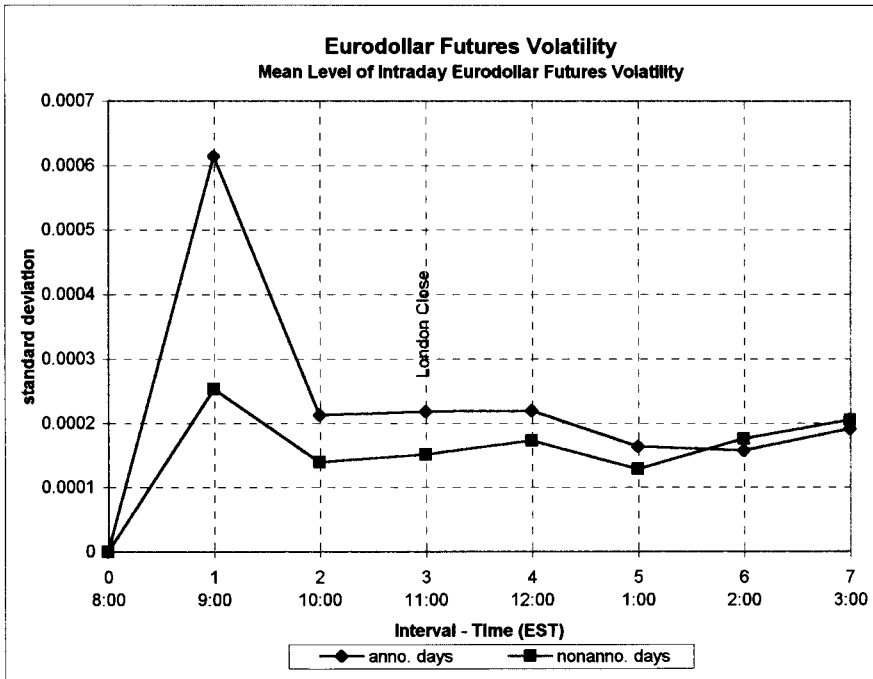


FIGURE 2

show two prominent spikes in volatility during the middle of the day that are followed by a substantial increase in volatility near the day's close (Figure 1). The timing of the first volatility spike in Figure 1 coincides with the close of Eurodollar futures trading in London at 11:00 AM, EST, leading KK&P to conclude that the two phenomena may be related.⁴ In

⁴Webb and Smith (1994) focus on Eurodollar futures, and also document intraday volatility patterns



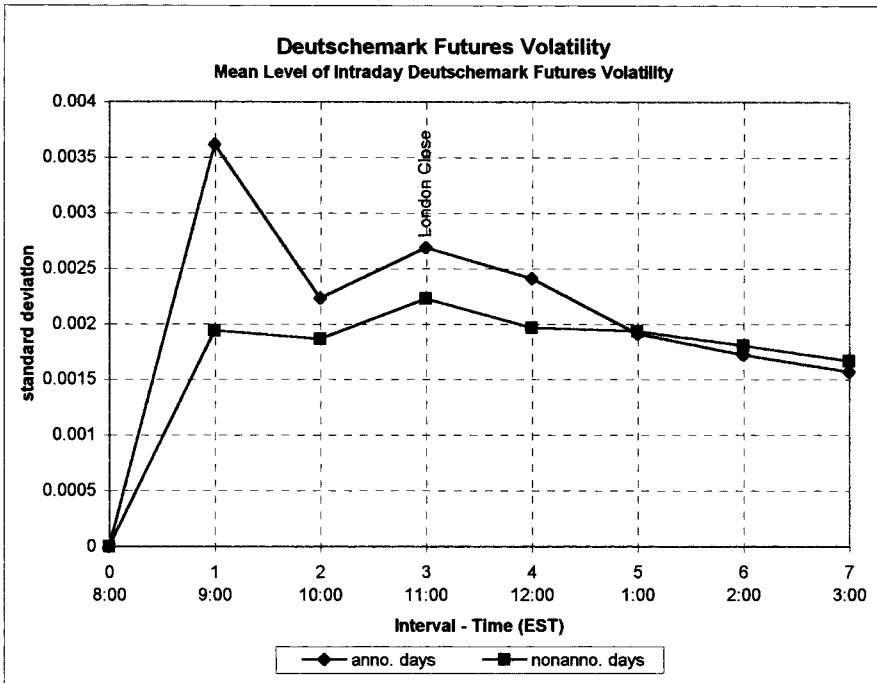
Hourly return standard deviations are calculated across daily observations from September 24, 1990, through June 20, 1993 for announcement days (anno.days) and nonannouncement days (nonanno. days). Each intraday interval represents approximately one hour of trading activity. The time reported is the ending time for the interval. Since the futures market opens at 8:20 a.m. (EST), the 8:20 - 9:00 return standard deviations are first computed. Under the assumption that hourly returns are independent, the 8:20 - 9:00 (40-minute) return standard deviations are converted to the 8:00 - 9:00 (60-minute) return standard deviations as follows:

$$(40\text{-min. return std.dev.}) \times [\text{square root of } (60/40)] = (60\text{-min. return std. dev.)}$$

Interval	anno.days (σ)	nonanno.days (σ)
0	0	0
1	.00061445	.00025312
2	.00021295	.00013899
3	.00021775	.00015178
4	.00021977	.00017317
5	.00016389	.00012889
6	.00015741	.00017578
7	.00019094	.00020529

Source: Crain and Lee (1995)

FIGURE 3



Hourly return standard deviations are calculated across daily observations from September 24, 1990, through June 20, 1993 for announcement days (anno.days) and nonannouncement days (nonanno. days). Each intraday interval represents approximately one hour of trading activity. The time reported is the ending time for the interval. Since the futures market opens at 8:20 a.m. (EST), the 8:20 - 9:00 return standard deviations are first computed. Under the assumption that hourly returns are independent, the 8:20 - 9:00 (40-minute) return standard deviations are converted to the 8:00 - 9:00 (60-minute) return standard deviations as follows:

$$(40\text{-min. return std.dev.}) \times [\text{square root of } (60/40)] = (60\text{-min. return std. dev.)$$

Interval	anno.days (σ)	nonanno.days (σ)
0	0	0
1	.00361932	.00194063
2	.00223465	.00186702
3	.00269052	.00222780
4	.00240767	.00196485
5	.00191153	.00193364
6	.00172138	.00180751
7	.00157242	.00167124

Source: Crain and Lee (1995)

FIGURE 4

contrast, the C&L pattern reflects no such midday spikes and only a slight increase in volatility at the close (Figure 3). For deutsche mark futures, KK&P again reveal a prominent midday volatility spike (Figure 2), whereas C&L show only a slight midday hump in volatility that surrounds the close of trading in London (Figure 4).

These apparent discrepancies in the studies of C&L and KK&P raise several issues. For example, has recent experience been more consistent with the intraday volatility patterns documented in either C&L or in KK&P? Do midday volatility spikes appear—as documented in KK&P—which represent significantly different levels of volatility from the behavior documented immediately before and after the spikes? Does the timing of any such volatility spikes coincide with the closing of associated markets in Europe? Are the patterns in intraday volatility robust over time? Are the differing methodologies employed in the two studies responsible for the seemingly divergent results? Or can the apparent discrepancies in results be attributed to nonstationary volatility patterns across the different sample periods studied in C&L and KK&P?

This article investigates these questions by applying the methodology of KK&P to explore the existence and robustness of possible midday spikes in intraday volatility patterns in Eurodollar and deutsche mark futures markets, over an extended sample period covering nearly seven years from 1 September 1988 through 20 June 1995. Results over this entire period confirm the volatility patterns documented in C&L, while also lending support to the existence of midday volatility spikes as documented in KK&P. For Eurodollar futures volatility, these midday spikes corroborate the results documented in KK&P and Webb and Smith (1994), whereas the deutsche mark futures volatility results are more similar to the midday hump in volatility appearing in C&L than the dramatic spike in KK&P.

This analysis of the entire sample period appears to reconcile the apparent discrepancies in the two respective studies. However, two features of these intraday volatility patterns call into question the causes and significance of the midday volatility spikes indicated in this analysis. First, the timing of the volatility spikes documented here is not precisely coincident with the close of trading in London. The two midday spikes in Eurodollar futures volatility found here and in Webb and Smith (1994)

that reveal two distinct spikes similar to those in KK&P (see their Figures 3–6), which are significantly different from the volatility behavior in surrounding intervals (see their Figures 7–9). For Webb and Smith, however, these two midday volatility spikes are substantially less dramatic than those occurring at the open and close, and their timing does not coincide precisely with the close of Eurodollar futures trading in London. Thus Webb and Smith remain silent on the possible causes of these midday volatility spikes.

occur immediately before and after London's market close, whereas the midday hump in deutsche mark futures volatility documented here and in C&L represents a broad rise in midday volatility that surrounds the close of trading in Europe by 90 minutes. This timing raises some question about the direct cause of these midday volatility spikes.

Second, for both Eurodollar and deutsche mark futures, these midday volatility conditions are not robust across yearly subsamples. Whereas a statistically significant midday spike appears in five of the eight yearly subsamples for Eurodollar futures, such a spike is statistically significant in only two yearly subsamples for deutsche mark futures. In addition, substantial variation appears across years, both in the level and in the nature of the volatility patterns experienced, especially for deutsche mark futures. This nonstationarity across yearly subsamples suggests that less weight should be placed on results from the entire sample period. Indeed, a main contribution of this article is to document the nonstationary nature of these intraday volatility patterns. This lack of robustness leads us to conclude that the apparent discrepancies in C&L and KK&P are due to nonstationarity in the volatility patterns, rather than to the different methodologies employed in C&L and KK&P.

DATA AND METHODOLOGY

Data

This article analyzes intraday volatility patterns in return volatility for the "lead" futures contract on Eurodollars and deutsche marks over the sample period—1 September 1988 through 20 June 1995. Time and sales data on the "lead" futures contract each quarter over this period were acquired from the Chicago Mercantile Exchange (CME). The nearby (next-to-expire) contract is typically the most actively traded contract. As a result, the CME designates by fiat the nearby to be the "lead" contract for most of its life as nearby. During this time, the nearby trades in a location in the pit designated for the "lead" contract. Shortly before the nearby contract expires, traders begin to roll over their positions and the concentration of trading volume shifts toward the second-to-expire contract. At some point prior to expiration of the nearby, the exchange redesignates the second-to-expire as the new "lead" contract. Coincident with this action, these two contracts switch trading locations within the pit and the new "lead" contract becomes the most actively traded contract. This redesignation typically occurs during the last two weeks of

trading prior to each quarterly expiration.⁵ Use of data for the “lead” futures contract each quarter over this seven-year sample period ensures we are investigating the nature of market behavior for contracts with high liquidity at any point in time. Furthermore, this procedure abstracts from potentially confounding behavior during the last week of trading that might accompany expiration in any nearby futures contract. This approach is consistent with that taken in Daigler (1997).

Methodology

This analysis is similar to the methodology applied in KK&P.⁶ First, time and sales data for the “lead” contract in each market were screened to generate a minute-to-minute futures price series by retaining the last futures price quote during each minute of every trading day. When no trade was recorded during a given minute, the old price was retained. The resulting minute-to-minute price series for each trading day was then converted into a minute-to-minute futures return series, as follows: $r_T = \ln(P_T/P_{T-1})$, where P_T is the last futures price quote during minute T .

Second, each trading day was split into intervals marked on the half hour. Because CME trading hours for both Eurodollar and deutsche mark futures markets extend from 8:20 AM to 3:00 PM EST, this procedure yielded fourteen intraday intervals for both futures contracts. Note that the first interval each day represents only 10 minutes of trading for these

⁵For deutsche mark futures, quarterly redesignation of the “lead” contract occurred throughout the 1980s whenever the CME determined that the second-to-expire contract was beginning to overtake the nearby as the most actively traded contract. In the early 1990s the CME changed policy to henceforth switch the designated lead contract on the Thursday prior to the second Friday before each expiration. In contrast, redesignation of the lead Eurodollar futures contract each quarter continues to be made by fiat on a discretionary basis by the CME.

⁶KK&P first construct a time series of futures prices using the last quoted price for each minute of every trading day throughout the sample. Then, segmenting each day into ten equal-length periods, they calculate the standard deviation of minute-to-minute returns for each intraday segment. The chart points in Figures 1 and 2 represent regression coefficients on ten dummy variables associated with the ten intraday subperiods—for Eurodollar futures and deutsche mark futures, respectively. These dummy coefficients trace out the systematic patterns in intraday volatility for these two markets during the fourth quarter of 1988.

C&L’s methodology is quite different. C&L begin with futures price series for each hour of trading, ignoring all intermediate price quotes between hourly observations. From this series of hourly futures prices across all trading days, they generate seven *daily* time series reflecting hourly rates of return experienced during each of the seven hours that span the typical trading day. That is, they generate one series reflecting rates of change in futures prices from the opening to 9:00 AM across all days in the sample, a second series reflecting rates of change from 9:00 AM to 10:00 AM—and so forth. From each of these seven subsamples for each hour of the day, they then compute the standard deviation across all daily observations. This methodology is similar to that of Engle, Ito, and Lin (1992), who model intraday volatility by partitioning the day into segments, and to Susmel and Engle (1994), who also model intraday volatility by using hourly returns.

two contracts, from 8:20 AM to 8:30 AM, whereas all remaining intraday intervals represent 30 minutes of trading activity.

Third, the sample variance of minute-to-minute returns was computed during each intraday time interval. This procedure yielded a time series of volatility measures covering each 30-minute interval throughout every trading day in the sample—for both Eurodollar and deutsche mark futures. The resulting time series of intraday volatility measures for each contract was then regressed on a set of fourteen dummy variables representing the different intraday time intervals, as follows:

$$s_{jt}^2 = \sum_{j=1}^{14} \alpha_j D_j + \varepsilon_{jt}, \quad (1)$$

where s_{jt}^2 = the sample variance for the j^{th} intraday interval on day t ;

D_j = 1 if the j^{th} intraday observation on day t is in interval j , and 0 otherwise;

ε_{jt} = error term for the j^{th} intraday observation on day t ;

j indexes the 14 intraday intervals during each trading day of the sample; and

t indexes the trading days in the sample period.

This analysis is analogous to a time series regression that measures potential recurring seasonal patterns in the data. The dummy coefficients (α_j) trace out any systematic pattern in intraday volatility recurring over the sample period investigated. This approach allows for a formal test of the statistical significance of any midday spikes in volatility that might appear in the form of unequal dummy coefficients during the middle of the trading day. The regression model is estimated for each contract over the entire sample period of nearly seven years, as well as over subsamples covering each of the eight calendar years that span the sample period. This approach enables an investigation of the evolution and robustness in any patterns in intraday volatility over the sample period.⁷

EMPIRICAL RESULTS

Eurodollar Futures

Panel A of Table I and Figure 5 list and plot the results for Eurodollar futures, estimated over the entire sample and over each yearly subsample.

⁷This analysis was also applied to subsamples of other lengths, as well as to subsamples restricted to periods under either daylight savings time or standard time in U.S. markets. Results support the conclusions made in this study.

TABLE I
OLS Regression Results Measuring Intraday Volatility Patterns

This table presents coefficient estimates and standard errors (in parentheses) from Ordinary Least Squares regression of the series of intraday volatility measures on a set of dummy variables representing all 30-minute intraday intervals. The model is estimated over each calendar year in the sample period, and over the entire sample period.

	Intraday Time Intervals														
Time:	8:30	9:00	10:00	10:30	11:00	11:30	12:00	12:30	1:00	1:30	2:00	2:30	3:00		
Dummy:	D1 ^a	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	R ²
Panel A: Eurodollar Futures (ED)															
Coefficient Estimates by Year: ^b															
1988	.386 (.102)	1.228 (.103)	.311 (.103)	.169 (.102)	.151 (.103)	.130 (.102)	.132 (.103)	.144 (.102)	.115 (.103)	.128 (.102)	.105 (.102)	.097 (.102)	.144 (.103)	.176 (.103)	.13
1989	.628 (.085)	1.936 (.085)	.528 (.085)	.386 (.085)	.407 (.085)	.256 (.085)	.231 (.085)	.426 (.085)	.288 (.085)	.221 (.085)	.255 (.085)	.253 (.085)	.290 (.085)	.395 (.085)	.18
1990	.559 (.026)	.696 (.026)	.341 (.026)	.333 (.026)	.323 (.026)	.252 (.026)	.239 (.026)	.290 (.026)	.258 (.026)	.215 (.026)	.215 (.026)	.224 (.026)	.258 (.026)	.368 (.026)	.41
1991	.547 (.052)	.935 (.052)	.292 (.052)	.309 (.052)	.268 (.052)	.230 (.052)	.200 (.052)	.254 (.052)	.184 (.052)	.173 (.052)	.181 (.052)	.213 (.052)	.201 (.052)	.266 (.052)	.16
1992	.630 (.034)	.831 (.034)	.367 (.034)	.305 (.034)	.354 (.034)	.249 (.034)	.253 (.043)	.308 (.034)	.238 (.034)	.228 (.034)	.204 (.034)	.214 (.034)	.254 (.034)	.335 (.034)	.32
1993	.446 (.017)	.527 (.017)	.247 (.017)	.210 (.017)	.254 (.017)	.189 (.017)	.165 (.017)	.150 (.017)	.148 (.017)	.140 (.017)	.126 (.017)	.144 (.017)	.167 (.017)	.256 (.017)	.48
1994	.584 (.029)	.772 (.029)	.352 (.029)	.316 (.029)	.430 (.029)	.288 (.029)	.291 (.029)	.275 (.029)	.245 (.029)	.219 (.029)	.259 (.029)	.242 (.029)	.294 (.029)	.350 (.029)	.40
1995	4.656 (.052)	1.046 (.052)	.466 (.052)	.368 (.052)	.537 (.052)	.408 (.052)	.314 (.052)	.284 (.052)	.272 (.052)	.244 (.052)	.259 (.052)	.269 (.052)	.306 (.052)	.429 (.052)	.41
ALL	.563 (.018)	.969 (.018)	.360 (.018)	.307 (.018)	.344 (.018)	.250 (.018)	.231 (.018)	.277 (.018)	.225 (.018)	.199 (.018)	.205 (.018)	.213 (.018)	.243 (.018)	.328 (.018)	.21
Chow Tests Across: All years: F = 7.81 (.001). First four years; F = 6.93 (.001). Last four years; F = 7.70 (.001). ^c															

TABLE I (Continued)
 OLS Regression Results Measuring Intraday Volatility Patterns

Panel B: Deutschemark Futures (DM)															
Coefficient Estimates by Year: ^b															
1988	.059	.232	.062	.056	.057	.055	.060	.055	.050	.047	.033	.037	.032	.036	.18
	(.020)	(.021)	(.020)	(.020)	(.021)	(.021)	(.021)	(.021)	(.020)	(.021)	(.020)	(.021)	(.021)	(.021)	
1989	.094	.204	.094	.081	.095	.089	.089	.085	.073	.068	.055	.060	.072	.059	.19
	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	(.012)	
1990	.049	.108	.060	.079	.078	.073	.079	.077	.078	.066	.057	.052	.053	.065	.25
	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	
1991	.075	.204	.127	.123	.130	.130	.116	.105	.087	.076	.068	.079	.061	.049	.30
	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	(.010)	
1992	.088	.242	.129	.117	.152	.153	.142	.124	.123	.083	.078	.062	.058	.068	.27
	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	(.013)	
1993	.065	.163	.097	.082	.108	.089	.085	.072	.062	.054	.046	.042	.038	.036	.31
	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	
1994	.044	.111	.065	.061	.076	.070	.084	.068	.064	.072	.068	.047	.041	.040	.23
	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	(.008)	
1995	.074	.247	.136	.156	.172	.152	.169	.180	.131	.093	.094	.085	.085	.063	.25
	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	(.022)	
ALL	.069	.179	.097	.094	.109	.103	.103	.094	.084	.071	.063	.058	.055	.053	.24
	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	(.004)	

Chow Tests: Across: All years; $F = 6.30$ (.001). First four years; $F = 4.56$ (.001). Last four years: $F = 9.21$ (.001).^c

^aThe Dummy coefficient, D1, represents the first intraday period from 8:20–8:30 am; D2 represents the second period, 8:30–9:00 am; D3 represents 9:00–9:30 am, and so forth.

^bEach yearly regression is estimated over all trading days during the given calendar year, except for the years, 1988 and 1995, which include abbreviated samples. The 1988 regression sample runs from Sept. 1–Dec. 31; the 1995 regression sample runs from Jan 1–Je. 20. Standard Errors appear in parentheses beneath parameter estimates. For ease of exposition, all coefficient estimates and standard errors are multiplied by 10^6 for ED futures, and by 10^8 for DM futures.

^cFor each contract three Chow tests are presented to test model stability across: (i) all calendar years in the sample (1988–95), (ii) the first four calendar years (1988–91), and (iii) the last four calendar years (1992–95).

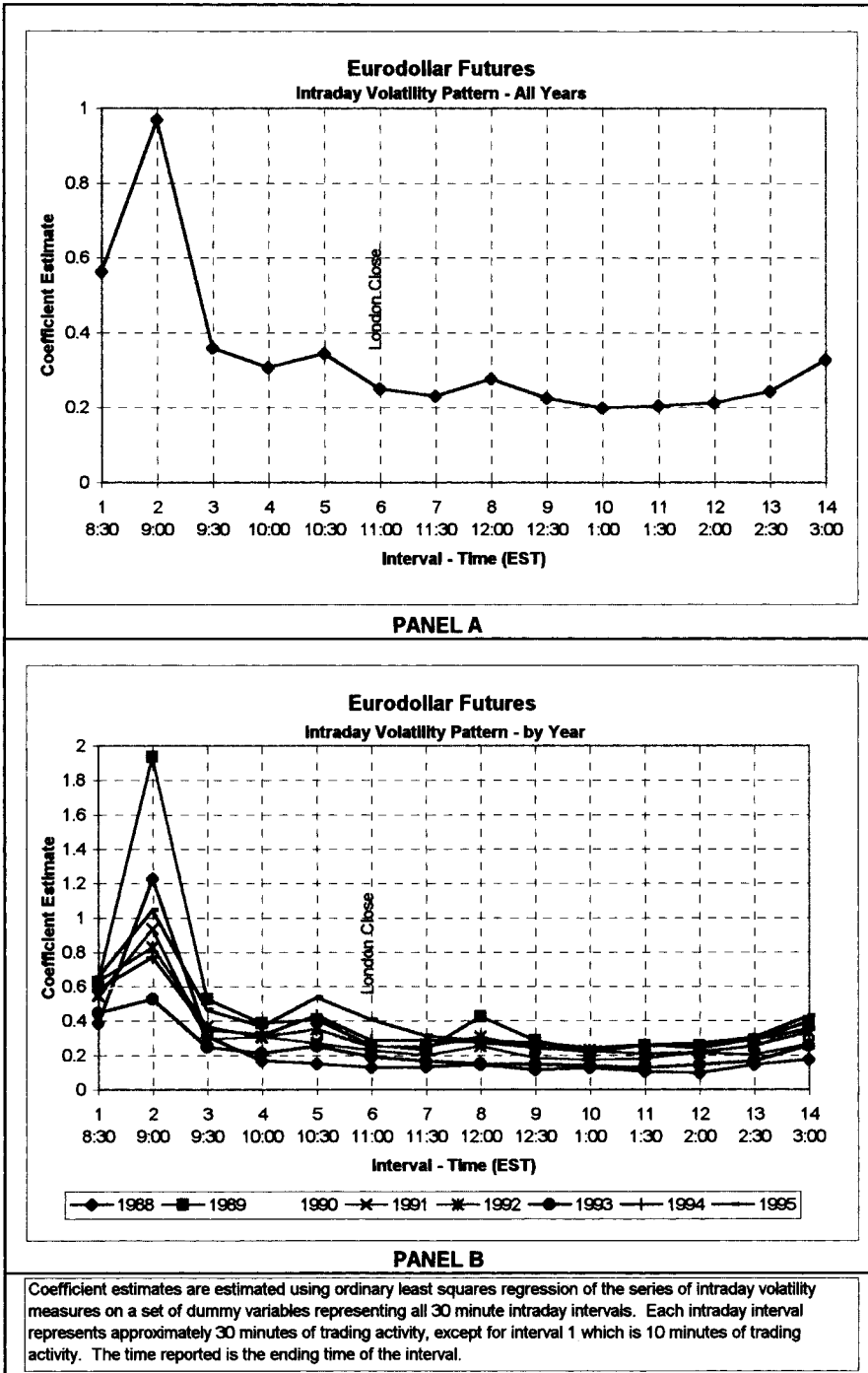


FIGURE 5

In Table I the point estimate is provided for each coefficient, along with its standard error. This presentation enables generation of 95% confidence intervals and tests of whether each coefficient differs significantly from the surrounding coefficients. These results reveal consistently high volatility at the beginning of the trading day. This high volatility manifests itself especially in the second intraday interval (after the first 10 minutes of trading). This high volatility from 8:30 AM to 9:00 AM quickly dissipates and demonstrates a tendency to decline through the day, until slight increases in volatility are evidenced during the last two intraday periods.

The overall pattern apparent in Panel A of Figure 5 is more consistent with that appearing in C&L (reproduced here in Figure 3) than with KK&P (reproduced here in Figure 1). This robustness across Figures 3 and 5 is noteworthy in light of the dramatic differences between the methodology employed by C&L and that applied here and in KK&P (see footnote 6).

We note a subtle discrepancy between the plots in Figures 3 and 5, however. In Figure 5 the tendency for volatility to decline throughout the day is interrupted for the entire sample, and for most yearly sub-samples, with two small spikes in volatility during the late morning in the U.S., specifically the fifth and eighth intraday intervals (from 10:00 AM to 10:30 AM and from 11:30 AM–12:00 PM EST, respectively). The timing and magnitude of these midday volatility spikes are consistent with those appearing in Webb and Smith (1994). We investigate the significance of these midday spikes by testing the following two null hypotheses:

- H_1 : There is no volatility spike between 9:30 AM and 11:00 AM; that is, dummy coefficients are identical for intraday intervals 4, 5, and 6.
 H_2 : There is no volatility spike between 11:00 AM and 12:30 PM; that is, dummy coefficients are identical for intraday intervals 7, 8, and 9.

Non-identical dummy coefficients would support the contention that these spikes at intervals 5 and 8 are, in fact, statistically significant.

These null hypotheses are investigated formally with the Wald F-test. Results of the F-tests for Eurodollar futures markets are presented in Panel A of Table II for each calendar year subsample, as well as for the entire sample. Panel A reveals that H_1 is rejected in five of the eight yearly subsamples at the 0.10 level or better, and for the entire sample at the 0.001 level.⁸ Interestingly, this first spike from 10:00 AM to 10:30 AM is

⁸Consistent with these results, Panel A of Table I reveals that the coefficient of D5 is at least two standard deviations above both coefficients of D4 and D6 for three yearly subsamples (1993, 1994, and 1995), as well as for the entire sample period. In addition, the coefficient of D5 is at least two standard deviations above D6 (but not D4) for two more yearly subsamples (1990 and 1992). These five yearly subsamples correspond to the significant F-tests in Panel A of Table II.

TABLE II
Testing for Mid-Day Spikes in Volatility

This Table presents tests for the significance of spikes in volatility during the middle of the trading day.

<i>By Individual Years</i>	<i>Panel A: Eurodollar Futures (ED)</i>	
	<i>H₁: D4 = D5 = D6^a</i> <i>9:30am–11:00am</i>	<i>H₂: D7 = D8 = D9^b</i> <i>11:00am–12:30pm</i>
1988	.036 (.965)	.021 (.979)
1989	.928 (.395)	1.384 (.251)
1990	2.786 (.062)*	.960 (.383)
1991	.567 (.567)	.480 (.619)
1992	2.358 (.095)*	1.156 (.315)
1993	4.005 (.018)**	.296 (.744)
1994	6.644 (.001)***	.659 (.517)
1995	2.911 (.055)*	.176 (.838)
1988–1995	6.902 (.001)***	2.493 (.083)*

<i>By Individual Years</i>	<i>Panel B: Deutschemark Futures (DM)</i>	
	<i>H₁: D4 = D5 = D6^a</i> <i>9:30am–11:00am</i>	<i>H₂: D7 = D8 = D9^b</i> <i>11:00am–12:30pm</i>
1988	.004 (.997)	.057 (.944)
1989	.336 (.715)	.465 (.628)
1990	.179 (.836)	.025 (.975)
1991	.146 (.864)	1.968 (.140)
1992	2.524 (.080)*	.695 (.499)
1993	3.267 (.038)**	2.389 (.092)*
1994	.917 (.400)	1.990 (.137)
1995	.220 (.802)	1.303 (.272)
1988–1995	3.653 (.026)**	5.508 (.004)***

^aThis column of F statistics tests the null hypothesis that the coefficients of three consecutive intraday dummy variables are identical, so that there would be no spike in volatility between 9:30 and 11:00 am. Under the null this statistic is distributed F with d1 and d2 degrees of freedom, where d1 = 2 for both contracts, and d2 = 24,066 for the full sample with Eurodollar futures, and 23,758 for the full sample with Deutschemark futures.

^bThis column of F statistics tests the null hypothesis that the coefficients of three consecutive intraday dummy variables are identical, so that there would be no spike in volatility between 11:00 am and 12:30 pm. Under the null this statistic is distributed F with d1 and d2 degrees of freedom, where D1 = 2 for both contracts, and d2 = 24,066 for the full sample with Eurodollar futures, and 23,758 for the full sample with Deutschemark futures.

*indicates significance at the .10 level; **significance at the .05 level; *** significance at the 0.1 level.

more pronounced during the most recent four years of the sample, since 1992. In contrast, results for H₂ are insignificant for all calendar year subsamples when investigated individually. When the entire sample period is scrutinized, however, the gain in degrees of freedom leads to a rejection of H₂ at the 0.10 level. Collectively, these results suggest the second spike from 11:30 AM to 12:00 PM is less pronounced than that between 10:00 AM and 10:30 AM.

In Panel A of Table 1, the adjusted R-square for the entire sample period, 1988–1995, is smaller than all but three of the analogous good-

ness-of-fit statistics for individual yearly subsamples. This outcome indicates a greater extent of unexplained variation in intraday volatility across the entire sample period than within most yearly subsamples, suggesting shifts in the pattern across years. Indeed, Chow tests reject the null hypotheses of model stability over all calendar years in the sample period, and over the first and last four years of the sample period. This result is not surprising, as the intraday pattern of Eurodollar futures volatility would not be expected to remain at stable levels over such a long period. Figure 5 reveals that this instability across years is especially apparent during intraday intervals two, five, and eight. Importantly, interval 2 represents the intraday period with the greatest volatility over the entire sample, as well as for all yearly subsamples, whereas intervals 5 and 8 represent the periods of the midday volatility spikes that represent the focus of this article.

It is striking that this evidence indicates these two volatility spikes occur at an earlier time than that suggested in KK&P—that is, just before and after the London close at 11:00 AM EST. This timing and pattern of intraday volatility raises the issue of why the Eurodollar futures market would exhibit a dip in volatility between these two spikes, during the window of time encompassing the close of Eurodollar futures trading in London. This issue should represent the focus of future inquiry. It is also interesting that the midday volatility spikes documented in KK&P are much larger in magnitude, relative to the high volatility at the beginning of the day, than those found over a more extended sample period here in Figure 5. In addition, the upturn in volatility at the end of the trading day documented by KK&P in Figure 1 is much more dramatic than the analogous upturn documented either in this work in Figure 5 or in the work of C&L in Figure 3.⁹

In sum, the results provided here corroborate some aspects of the intraday volatility patterns in Eurodollar futures volatility documented in each of the two previous studies by KK&P and C&L, as well as in the prior work of Webb and Smith (1994). As a result, this evidence helps to reconcile the apparent discrepancies in these previous studies, by suggesting the general intraday volatility pattern documented by C&L prevails and by corroborating the existence of midday volatility spikes as revealed by KK&P and Webb and Smith (1994). Also noteworthy is that this work does not find a statistically significant volatility spike in 1988, the period that corresponds most closely with that analyzed in KK&P.

⁹The two midday spikes in Eurodollar futures volatility appearing in Webb and Smith (1994) more closely resemble the results here in Figure 5 than those from KK&P (reproduced here in Figure 1). On the other hand, Webb and Smith find a greater upturn in volatility at the day's close—which more closely matches that of KK&P in Figure 1 than that appearing here in Figure 5.

Furthermore, the timing of the volatility spikes documented here is not coincident with the close of trading in London; the level of this volatility pattern shifts substantially across years, thus calling into question the causes and significance of these midday volatility spikes.

Deutsche Mark Futures.

Panel B of Table I and Figure 6 list and plot the results for deutsche mark futures over the entire sample period and for each yearly subsample. As with Eurodollar futures in Figure 5, Figure 6 indicates high volatility in deutsche mark futures during the second intraday interval (after the first 10 minutes of trading). This high volatility quickly dissipates to a lower level of volatility between 9:00 AM and 10:00 AM. However, for deutsche mark futures this period is followed by a small rise in volatility that extends over several midday intervals that surround the close of trading in London, before beginning a downward trend in volatility that continues throughout the remainder of the day.

The adjusted R-square for the entire sample in Panel B of Table I is smaller than all but three analogous measures for the yearly subsamples. As with Eurodollar futures, this result indicates substantive shifts in the deutsche mark futures volatility patterns across years, which is verified by the Chow tests in Table I. Indeed, Panel B of Figure 6 reveals that these shifts are substantially greater in magnitude than those indicated for Eurodollar futures in Figure 5.

On the other hand, one consistent feature of the deutsche mark volatility patterns across several years in Panel B of Figure 6 is the small rise in volatility that extends over intraday intervals 5-8, surrounding the time of the close of London markets. This midday aberration in deutsche mark futures volatility resembles the mild hump documented in C&L (Figure 4), more than the dramatic spike revealed by KK&P. To assess the statistical significance of this midday aberration in volatility, we test the same two hypotheses (H_1 and H_2) previously investigated with regard to Eurodollar futures (presented in Panel A of Table II). In this case these tests effectively examine whether the left and right sides of this midday hump in volatility are flat (that is, there is no hump), respectively.

Test results are provided in Panel B of Table II for the entire sample and for all yearly subsamples. Results reject H_1 in just two yearly subsamples at the .10 level of significance, although H_1 is rejected for the entire sample at the 0.05 level. Similarly, H_2 is rejected in one yearly subsample at the 0.10 level and for the entire sample at the 0.01 level. The collective results provided in Panel B of Tables I and II, and in Figure 6, characterize

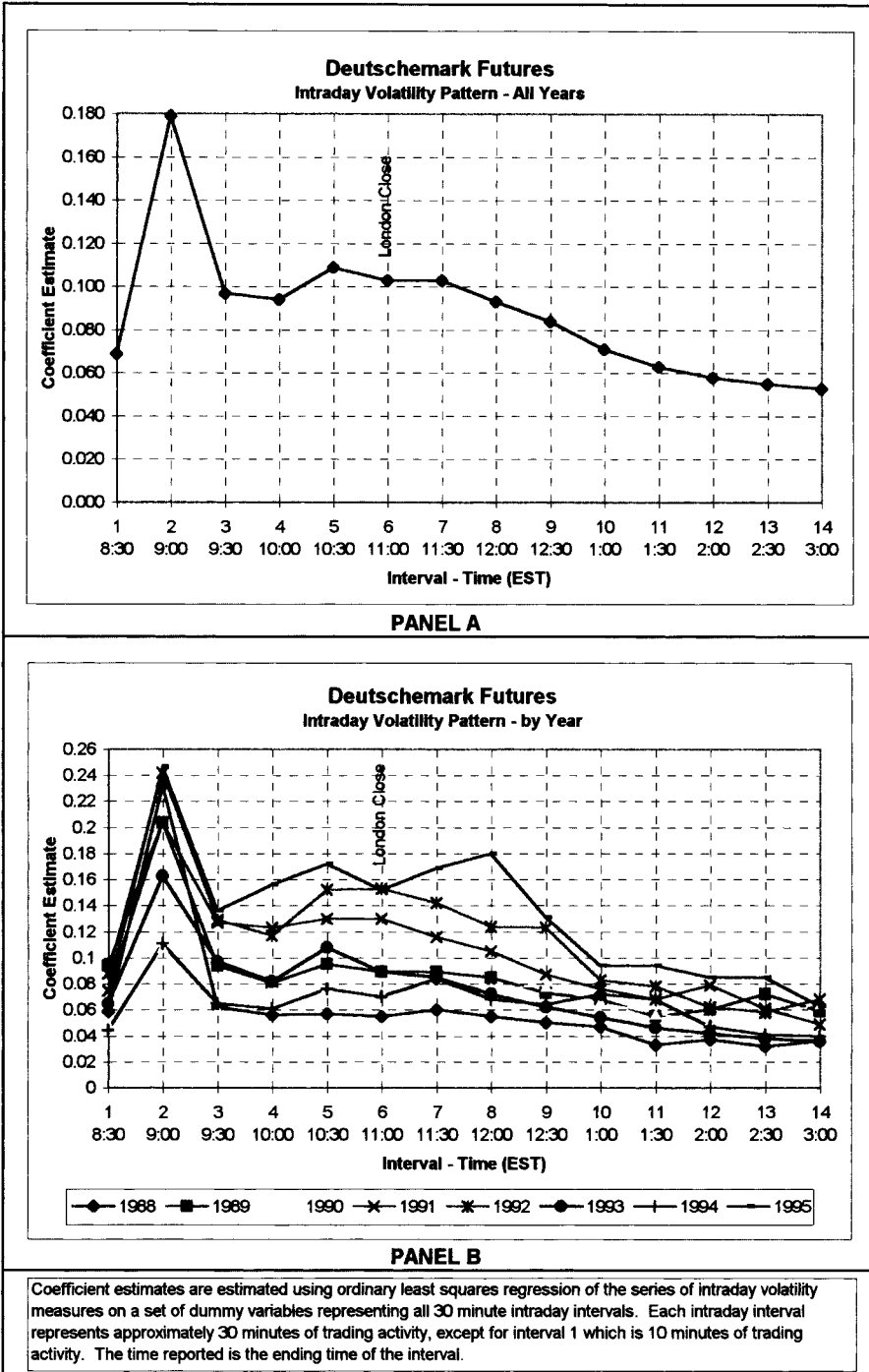


FIGURE 6

a pattern of intraday volatility that is quite unstable across years. The extent of these shifts in deutsche mark futures volatility patterns across years tends to swamp any systematic midday spike that occurs within each yearly intraday volatility pattern. This instability suggests that less weight should be placed on the results for the entire sample.

In sum, as with Eurodollar futures, results for deutsche mark futures tend to corroborate the general pattern of intraday volatility documented by C&L, whereas results also reveal a mild hump in midday volatility that is statistically significant over the entire sample, consistent with the results of KK&P. On the other hand, this volatility hump does not occur precisely when the London markets close, but instead extends over 90 minutes surrounding the close of trading in Europe. Furthermore, this midday volatility hump is small in magnitude relative to the sizable shifts in the entire volatility pattern across years. These observations call into question the causes and significance of this midday aberration in deutsche mark futures volatility.

SUMMARY AND CONCLUSIONS

Two previous studies, by Crain and Lee (C&L, 1995) and by Kawaller et al. (KK&P, 1994), exhibit seemingly divergent results regarding the existence of midday volatility spikes in Eurodollar and deutsche mark futures markets. This article investigates the nature and robustness of these intraday volatility patterns. Specifically we employ time and sales data from 1 September 1988 through 20 June 1995 to test for the existence and robustness of midday volatility spikes in these two markets. Results for the entire sample period corroborate some aspects of the volatility patterns that appear in each study, and thus help to reconcile the seemingly divergent results of C&L and KK&P. On the other hand, the clear non-stationary nature of these volatility patterns across years reveals that the magnitude of any midday volatility spikes is dwarfed by shifts in the volatility pattern over time. Also, the timing of these midday volatility spikes does not precisely match the close of trading in London, calling into question the cause of this phenomenon. This timing conundrum suggests that, although London's close likely has an influence on volatility patterns, it is not the sole influence. Other factors appear to be working as well; however, the nature of these market forces remains an open question.

For Eurodollar futures, the general intraday pattern in volatility documented here most closely follows that provided by C&L. This pattern indicates high volatility shortly after trading opens, that dissipates quickly

and tends to decline until the last hour of trading, when it again turns up slightly. On the other hand, these results also corroborate the existence of midday spikes in Eurodollar futures volatility that occur during the late morning in the U.S. markets, as documented in KK&P and in Webb and Smith (1994). One midday volatility spike is statistically significant over the entire sample period, as well as over five of the eight calendar-year subsamples, including the most recent four years since 1992. This outcome suggests these midday volatility spikes have become more prevalent in recent years. On the other hand, the timing of these volatility spikes does not precisely match the close of trading in Europe, instead occurring just before and after London's close. Furthermore, there is substantial variation across years in the level of this Eurodollar volatility pattern.

Results for deutsche mark futures similarly tend to follow the general pattern of intraday volatility documented by C&L. The day begins with high volatility that tends to decline thereafter. This decline is interrupted, however, by a rise in volatility at midday. This volatility spike is statistically significant over the entire sample period, but when examined on a year-by-year basis, significance is documented in only two of the eight calendar year subsamples. The character of this volatility rise more closely resembles the mild hump appearing in C&L than the dramatic volatility spike revealed in KK&P. Moreover, the timing of this volatility hump extends over several intraday intervals surrounding the close of deutsche mark futures trading in London. Most importantly, this volatility pattern exhibits great variation across years, which swamps the relatively small magnitude of this midday hump in volatility during any given year. This clear nonstationary nature of the intraday volatility pattern suggests that less weight be placed on results from the entire sample period.

It is noteworthy that the overall patterns for both Eurodollar and deutsche mark futures volatility tend to conform more closely to those documented in C&L, even though the methodology of KK&P is applied here. This observation, combined with the lack of robustness across years, leads us to conclude that the apparent discrepancies in C&L and KK&P are due to nonstationarity in the volatility patterns, rather than to the different methodologies employed in C&L and KK&P. Furthermore, this nonstationarity—along with the observation that the timing of these midday volatility spikes does not precisely match the close of trading in London—calls into question the causes and significance of the midday volatility spikes appearing in the data.

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