A Microstructure Analysis of the Carbon Finance Market

Don Bredin
University College Dublin *

Stuart Hyde
University of Manchester†

Cal Muckley
University College Dublin‡

Preliminary and Incomplete

Abstract

The European Union's Emissions Trading Scheme is the key policy instrument of the European Commission's Climate Change Program aimed at reducing greenhouse gas emissions to eight percent below 1990 levels by 2012. The key asset traded under the scheme is the European Union allowance (EUA). This article examines the market microstructure focussing on the interaction between trading volume, duration and price volatility.

Keywords: CO2 prices, EU ETS, Energy, Kyoto Protocol, Market microstructure.
JEL Classification: G13, G14, G19.

---

*E-mail: don.bredin@ucd.ie. Corresponding author: Don Bredin, School of Business, University College Dublin, Blackrock, Dublin, Ireland. The authors would like to thank Ike Johnson for research assistance.

†E-mail: stuart.hyde@mbs.ac.uk

‡E-mail: cal.muckley@ucd.ie.

1 Introduction

In January 2005 the European Union (EU) emissions trading scheme (ETS) was introduced formally. The scheme has been instigated as part of the EU agreement to cut worldwide emissions of carbon dioxide (CO_2) within the Kyoto Protocol. Under the Kyoto agreement, the EU has committed to reduce greenhouse gas (GHG) emissions by eight percent (relative to 1990 levels) by 2008-2012. The scheme issues a restricted amount of emission allowances to firms on an annual basis. At the end of the year firms must hold the required amount of emission permits to meet their emissions of CO_2 over the previous year.[1] The ETS allows firms to trade the amount of emission permits that they hold and as a result has applied a market value to this externality. In the EU ETS context the first phase (pilot) of trading was 2005-2007 and the second one (Kyoto), which coincides with the first compliance period of the Kyoto Protocol, is 2008-2012. The third European trading phase will commence in 2013. Non-compliance with the commitments will result in a penalty of 40 (100) euros per tonne of CO_2 produced for the first (second) commitment period. The aim of the ETS is that this cost will encourage firms to reduce their emissions. Paolella and Taschini (2008) highlight that the ultimate aim of this scheme (as well as the US CAAA-Title IV scheme) must be to create an environment where there is scarcity of allowances which will lead to an upward trend in prices. As a result we might expect to see mean reversion around an upward trend. There has been a considerable amount of uncertainty associated with the price of CO_2 emissions over its short life to date. [2]

Our paper will examine the performance of phase 1 from a market microstructure perspective with the aim of understanding the information assimilation process, liquidity and the degree of market efficiency during the pilot phase. A duration (time between consecutive trades) based model is adopted to examine the relationship between volume and volatility. Our analysis is carried out on phase 1 EU ETS futures and we focus on futures

[1] A report must be submitted to verify the emissions in any year by the 31^{st} March of the following year.

[2] The trading scheme also provides developing business opportunities for intermediaries and service providers. The pricing behavior of CO_2 emissions will be particularly important to these players.

data provided by the European Climate Exchange (ECX).[3] Convery and Redmond (2007) highlight that while emissions reduction has been the principal aim for the Kyoto phase, the main objective of the pilot phase was to get the scheme up and running. In particular that it would be fully operational by 2008, the start of phase 2 (Kyoto phase).[4] Given that markets (both spot and future), registries and monitoring, reporting and verification has been established, one may argue that the principal aim of phase 1 has been achieved.

What micro structure issues will we deal with and why are they important. What are the implications for the development of the market.

A number of studies have examined the performance of phase 1, however all have adopted relatively low frequency data. Recent studies include Paolella and Taschini (2008), Daskalakis et al (2009) and Benz and Trück (2009) examine the time series properties of a range of different EU ETS instruments.[5] For example Benz and Trück (2009)adopt a pure time series approach and take account of the non-normality associated with the EU allowance returns and find evidence of regime switching.[6] The empirical studies to date have highlighted the difficulties associated with phase 1 (pilot phase). In particular there was considerable uncertainty and volatility associated with the market price of EUA's. In April 2006, coincident to the unofficial release of the 2005 emissions data by some of the EU member states the price of EUA's collapsed. EU ETS spot prices had reached a high of 30.50 euro prior to April 2006. Following the official release by the EU commission on the

[3]76% of the volume of trades EUA's are futures contracts, while of that 96% are traded on ECX. The remainder is traded on the European Energy Exchange (EEX) and Nordpool (see Mansanet-Bataller and Pardo, 2008).

[4]Ellerman and Buchner (2006) estimate that the phase 1 ETS has been responsible for reducing CO_2 emissions by between 50 and 200 million tonnes.

[5]Paolella and Taschini (2008) examine both SO_2 (in the US) and CO_2 (EU) spot price dynamics.

[6]Redmond and Convery (2006) examine EU ETS using daily data over the period 1^{st} December 2004 to 31^{st} July 2006. Unlike the previous cited studies which adopted a pure time series approach, the behaviour of the price of carbon is examined in relation to energy commodities, meteorological factors and a number of other variables.The other variables include for example dummy variables to take account of policy and regulatory issues.

15th May 2006, showing a larger than expected surplus in the market, the spot price fell to 15.63 euro on the 17th May 2006. Given that banking EUA's was prohibited between phases, the price eventually converged to close to zero at the end of phase 1. Overall for phase 1, it would appear that the cap placed on emissions was far too lax and so downward pressure on the price continued.

Clearly a number of difficulties remain. These include the fact that the cap was only aimed at large emitters from the power and heat generation industries and in selected energy intensive industries.[7] As has been highlighted earlier the over allocation of allowances has been problematic. The national allocation plans (NAP) submitted by member states to the European Commission were not reviewed in phase 1 and these were distributed free of charge by member states to the emitting firms.[8] The only study that has addressed the market microstructure issues for this market has been Benz and Hengelbrock (2008). The authors find evidence of increased liquidity for both the ECX and Nord pool, with particularly strong evidence for the considerably larger ECX market.[9] The ECX also represents a price leader in particular for the recently traded contracts (December 2007 and 2008).

2 Econometric Methodology

2.1 Empirical Issues

Market microstructure research must confront the problems generated by the fact that transactions data arrives at irregularly spaced intervals in time. Many studies simply ignore the time variation between successive trades, and analyze the data utilizing econometric techniques more appropriate for equally spaced observations. We maintain that this

[7]The European Commission (2005) has estimated that these installations account for 45% of CO_2 emissions. Airlines will be included in the next phase of the EU ETS, from 2013-2020.

[8]Member states were allowed to auction up to 5% of their total allowance allocation in phase 1 (Convery and Redmond, 2007). To date Denmark, Hungary, Ireland and Lithuania have used auction provisions.

[9]Both spot and futures contracts are traded on the Norwegian platform Nord Pool, which has a market share of 12.5% on the futures market.

approach may result in a significant loss of information, since the elapsed time between consecutive trades (duration) may convey important information about the state of the market. Two approaches have been proposed to accommodate this concern. First, Engle (2000) argues that variables in empirical microstructure models should be adjusted for duration in order to obtain time-consistent parameter estimates. In this vein, Xu et al. (2006) incorporate a time factor by standardizing both volume and volatility with respect to elapsed time (trade duration) thereby creating time consistent measures for empirical tests. The hypothesis is that the longer the interval over which a return is measured, the higher the probability of pertinent news arrival and the greater the ensuing trade size and volatility. In this spirit, we begin our analysis by utilising a time consistent structural vector autoregression (VAR) model to characterize the dynamic relationship between our duration-based volatility and volume measures.

Second, Engle and Russell (1998) and Dufour and Engle (2000) explicitly incorporate the duration between trades as an endogenous variable in a microstructure model. The inclusion of a duration variable not only addresses the estimation problems associated with irregularly occurring observations, but more importantly it also permits the information conveyed by duration to be explicitly incorporated in the modeling framework. In order to better understand the dynamic relationship between duration, volume, and volatility, we further extend the analysis by specifying a trivariate VAR framework in which we explicitly model duration. Key questions will be the whether the MDH applies in the case of EUA's and how do variations in the pattern of informed and liquidity trading influence EUA futures price volatility and the observed volatility-volume relationship?

Finally, given our trivariate VAR formulation, we then modify our variable definitions in a manner enabling us to explicitly account for the interaction between the marginal distributions of the trade characteristic variables in a manner suggested by Manganelli (2005). This modeling framework illuminates issues concerning: (i) the relationship of trading volume to risk; (ii) the percentage of price volatility attributable to information-based trading; and (iii) the length of time taken for prices to incorporate new information.

2.2 The VAR models

Initially, we formulate a bivariate VAR model where volume and volatility are standardized per unit of time, thereby accommodating the scale effect of duration on trade volume and volatility.

$$
\begin{aligned}
z_{d,t} &= \sum_{i=1}^{p} a_{zi} z_{d,t-i} + \sum_{i=0}^{q} (b_{zi} + c_{zi}\tau_{t-i}) v_{d,t-i} + u_t \\
v_{d,t} &= \sum_{i=1}^{p} a_{vi} z_{d,t-i} + \sum_{i=1}^{q} (b_{vi} + c_{vi}\tau_{t-i}) v_{d,t-i} + \epsilon_t
\end{aligned} \tag{1}
$$

where $z_{d,t}$ and $v_{d,t}$ are duration-based volatility and volume, respectively.[10] Specifically, if $d_t = T_t - T_{t-1}$ is duration, the elapsed time between consecutive trades at T_t and T_{t-1}, then $z_{d,t} = ln[\frac{Z_t}{d_t}]$ is the log volatility per unit of time, and $v_{d,t} = ln[\frac{V_t}{d_t}]$ is the log volume per unit of time. Here, we measure volatility, Z_t , by the absolute value of returns, $|r_t|$ and the volume variable, V_t , by the trade size at time t. The order of the lag length for the duration-based volatility and volume variables, (p, q), are determined on the basis of the Akaike information criteria (AIC). Following Xu et al. (2006) we include an interaction term $\tau_{t-i}(\tau_t = ln(d_t))$, that allows the volume to vary with duration in both equations. [11] As can be seen from equation 1 $z_{d,t}$ and $v_{d,t}$ are driven by two uncorrelated random shocks; an informed traded shock, u_t and an uninformed traded shock, ϵ_t. Easley and OHara (1992) argue more informed traders tend to trade at short durations, thus we expect larger volumes to be traded at shorter durations. Hence, the impact of volume on prices should be greater at shorter durations.

[10]Both duration-based volatility and volume are per unit time and in log terms to ensure that the variables are positive.

[11]It is then possible to examine whether duration between trades affects price adjustment to trades in the volatility equation. In the volume equation, the interaction term allows us to observe the correlation between current and past volume.

The ordering of the variables is based on the assumption that a shock to duration would be transmitted to trading volume and price volatility. The intuition is that, as suggested by market microstructure theory, with the arrival of new information (time dependent), informed traders choose to trade various volumes of futures contracts. Depending on the nature of the information (good or bad news), as well as the demand/supply nexus, agents execute either large numbers of trades over a short time frame (high trading activity) or fewer trades over a longer time interval (low intensity).[12] Although one could argue that a trader, a priori, decides on his/her trading volume given his/her demand needs, we conjecture that this notion ignores the effect that news has on a priori beliefs and the timing of trades. The ordering of the variables in above (and in the extended VAR later) is theoretically informed. In Kyle (1985), insider (informed) traders act strategically. They rationally anticipate the impact of orders on prices, by conditioning on the behaviour of other market participants (namely, the market maker and uninformed traders). As new private information arrives, informed traders review the existing price quotes of a specialist market maker and select the amount of shares which maximizes their informational advantage to trade. Easley and OHara (1992) argue that the timing of an order placement also conveys relevant information to the market maker, and will be internalized by an informed trader when deciding their order placement strategy. Hence, volume and duration interact to influence price (volatility) at time t. Further, Manganelli (2005) highlights that although an informed trader may prefer to exploit their informational advantage by trading a larger amount of the asset, initiating this strategy would immediately reveal their inherent informational advantage and the market maker would adjust quotes accordingly. Thus, in order to disguise their investor type, an informed trader may segment their order flow into a sequence of smaller trades separated in time. The subsequent market trading intensity then determines the amount of shares exchanged at each price. Consequently, given informed traders always trade to exploit their informational advantage, subsequent to the arrival of price relevant information, expected duration will fall and expected volumes will rise, making

[12] The underlying assumption is that liquidity (noise) agents, trade with constant intensity.

trade more likely. Thus we adopt a causal ordering such that causality runs from duration to volume, and from both duration and volume to volatility.[13] In addition, based on both the mixture of distribution and sequential arrival of information specifications, we expect a positive relationship between volatility and volume. However, while the MDH suggests a positive contemporaneous causal relationship between volume and volatility, the sequential arrival of information model implies a leadlag relationship in both directions (bidirectional causality) between these two variables.

Given duration is informative about an assets true value (Diamond and Verrecchia, 1987; Easley and OHara, 1992), it follows that duration should interact with volume to influence the characteristics of asset prices. To capture these interactions, we extend the VAR analysis to include time as an endogenous variable. The VAR for duration, d_t, volume, V_t , and volatility, Z_t , is:

$$\begin{aligned} d_t &= \sum_{i=1}^{p1} \gamma_i d_{t-i} + \sum_{i=1}^{q1} \rho_i V_{t-i} + \sum_{i=1}^{r1} \delta_i Z_{t-i} + \varepsilon_t \\ V_t &= \sum_{i=0}^{p2} \lambda_i d_{t-i} + \sum_{i=1}^{q2} \zeta_i V_{t-i} + \sum_{i=0}^{r2} \phi_i Z_{t-i} + \eta_t \\ Z_t &= \sum_{i=0}^{p3} \beta_i d_{t-i} + \sum_{i=0}^{q3} \theta_i V_{t-i} + \sum_{i=1}^{r3} \alpha_i Z_{t-i} + \zeta_t \end{aligned} \qquad (2)$$

where the lag orders are determined by the Akaike information criteria (AIC). The return volatility processes in equations (1) and (2) are a generalization of the return process in the traditional MDH model, which postulates that return volatility depends on the flow of information and a random disturbance term. The return volatility process in the MDH framework can be written as:

[13] This is consistent with Manganelli (2005, p.382) who highlights (i) the duration between trades can affect prices, (ii) duration should be correlated with volume, and (iii) both duration and volume should be correlated with transaction price variances.

$$Z_t = K_t + \upsilon_t \tag{3}$$

where $K_t = lnk_t^{1/2}$, k_t is the latent information flow and υ_t is the disturbance term. In the traditional MDH model, return volatility is related to the latent information flow k_t concurrently, and the disturbance term is serially independent. The volatility process in equation (2) generalizes the MDH volatility process in equation (3) in several ways. First, it permits a lagged dependence in t Z . This generalization is quite appropriate given that empirical evidence suggests strong volatility persistence, even after controlling for the effect of information flow. The cause of volatility persistence is usually attributed to one or a combination of microstructure imperfections, inventory control, exchange-mandated price smoothing, and/or lagged adjustment to information among others. In the extreme case, where the serial dependence is absent, the values of the lagged coefficients, a ' s and b ' s , in equation (2) will be insignificantly different from zero and the model simply degenerates to the traditional MDH volatility process. It follows that the specification is more general in that it can accommodate serial dependence in volatility. Second, in this three variable formulation, the latent information is linked to trading volume and duration which is consistent with the argument that information induces trades, which in turn, move prices. Third, the VAR model permits lagged information effects on volatility, thereby removing the stringent restriction imposed by the MDH model that information must be instantaneously impounded into prices. The present model accommodates a process of dynamic adjustment or a learning effect in relation to the new information, so that return volatility is affected by lagged information. Finally, empirical tests of the MDH model at the intraday level typically use transaction data aggregated up to fixed intraday intervals. Naturally, there is a loss of information in this aggregation. This loss occurs partly due to the large number of zeros, making econometric analysis extremely complex if the intervals are small. In contrast, the three variable VAR model is directly based on irregularly spaced transaction data, which is free from the problem of temporal aggregation. At the same time it accounts for transaction time, by the inclusion of duration.

2.3 Marginal Distributions Model: Duration, Volume & Volatility

Duration, trade volume and return volatility share common data series properties in that they are autocorrelated, heteroskedastic, and persistent and can be modeled as GARCHlike processes. Manganelli (2005) posits that the three marks of the trading process duration (d_t), volume (v_t) and return (r_t) can be modeled as follows:

$$(d_t, v_t, r_t) \sim f(d_t, v_t, r_t|\Omega_t; \theta) \tag{4}$$

where Ω_t represents information at t, and θ is a vector incorporating the parameters of interest. Under the hypothesis that causality runs from duration to volume and from duration and volume to the volatility of returns, this distribution can be broken down into the product of three components: the marginal distribution of durations $\times$ the conditional distribution of volumes on durations $\times$ the conditional distribution of returns on volumes and durations:

$$(d_t, v_t, r_t) \sim g(d_t|\Omega_t; \theta_d) \cdot h(v_t|d_t, \Omega_t; \theta_v) \cdot k(r_t|d_t, v_t, \Omega_t; \theta_r) \tag{5}$$

According to Manganelli (2005), the chosen parameterization of the model reflects the various strategic models in the market microstructure literature. For example, in Kyles (1985) model, informed traders act strategically taking into account the effect their orders have on price by conditioning on the behavior of both the market maker and uninformed traders. In addition, according to Easley and OHara (1992), since the timing of trades conveys meaningful information to the market maker, informed traders take this into accounting when timing their trades. Further, when faced with new information, the informed trader, in an attempt to hide his/her trader type, may split large orders into many smaller buy and sell orders. Thus this trading strategy will impact on the trading intensity and the duration of trades. Consequently it is evident that there exists an interplay between duration, volume and volatility. The densities in equation (5) may be represented by GARCHlike models: an Autoregressive Conditional Duration (ACD) model for duration, an Autoregressive Conditional Volume (ACV) model for volume and a GARCH model for returns. The respective conditional expectations are ψ , ϕ and σ^2 such that the models can be represented (Manganelli, 2005):

$$\begin{aligned} d_t &= \psi_t(\theta_d; \Omega_t)\epsilon_t \quad \epsilon_t \sim iid(1, \sigma_\varepsilon^2) \\ v_t &= \phi_t(\theta_v; d_t, \Omega_t)\eta_t \quad \eta_t \sim iid(1, \sigma_\eta^2) \\ |r_t| &= \mu_t + \sigma_t(\theta_y; d_t, v_t, \Omega_t)\zeta_t \quad \zeta_t \sim iid(0, 1) \end{aligned} \tag{6}$$

In practice, restricting each model to 1 lag and allowing for interaction between the processes, we estimate the following:

$$\begin{aligned} \psi &= \omega_d + \beta_d\psi_{t-1} + \alpha_d d_{t-1} + \delta_{d1}v_{t-1} + \delta_{d2}|r_{t-1}| \\ \phi_t &= \omega_v + \beta_v\phi_{t-1} + \alpha_v v_{t-1} + \delta_{v1}d_{t-1} + \delta_{v2}|r_{t-1} + \delta_{v3}|r_{t-1}| \\ \sigma_t^2 &= \omega_r + \beta_r\sigma_{t-1}^2 + \alpha_r|r_{t-1}| + \delta_{r1}d_{t-1} + \delta_{r2}d_{t-1} + \delta_{r3}v_{t-1} + \delta_{r4}v_{t-1} \end{aligned} \tag{7}$$

3 Data and Empirical Results

3.1 Data

We adopt intra-day transaction data for EUA futures contracts with a December 2005, 2006, 2007 and 2008 expiry.[14] One futures contract corresponds to 1,000 EUA's and represents the right to emit 1,000 tonnes of CO_2. The sample size for our four contracts are as followings; December 2005 (22^{nd} April 2005 to 19^{th} December 2005), December 2006 (16^{th}

[14]Contracts with a quarterly expiry exist (March, June, September and December), however the December expiry contracts are far more liquid and hence we focus on these instruments.

June 2005 to 18^{th} December 2006), December 2007 (3^{rd} June 2005 to 18^{th} December 2007) and December 2008 (28^{th} September 2005 to 18^{th} May 2007. The contracts expire on the last Monday of December, while settlement is three days after the last trading day. The data is taken from the continuous trading session, which runs from 7am to 5pm (UK local time). The ECX has currently over 100 members trading EUA's.[15] Incoming orders on the ECX are binding until the end of the trading day if they have not been executed, changed or canceled. The minimum tick size is 0.01 euro per tonne of CO_2, while a range of order types are available including limit, market and stop orders. The annual fee for ECX members is 2,500 euros, while the trading and clearing fee per contract is currently 3.50 euros. There are currently (introduced in December 2008) 3 market makers for the ECX (Five Rings Capital (formerly Jane Street Global Trading), Saxon Finance and RNK Capital). The market maker is required to provide bid and ask quotes for at least 85% of the trading time between 8am and 5pm (UK local time) and are required to respond to quote requests within five minutes.

The data includes comprehensive information relating to all transactions, maturities, trade prices, opening prices and trading volume for four different futures instruments traded on Phase 1 of the EU ETS. To prepare the data for the analysis, we first sum the trading volumes when we detect a series of equal recorded prices for the same contract maturity which occur at the same time. The summation of trading volumes can be motivated by the practice in the management of the electronic book. This consists of utilizing the existing liquidity that is available in the sense that a trader can choose to split a large transaction into a series of smaller transactions and trading with different counterparties. We then compute the duration between trades, treating the overnight period as if it did not exist. By eliminating the duration occasioned by the overnight period, we remove the suggestion that this period contains no price relevant news, which would otherwise be implied by including the unadjusted overnight duration. In table 1 we report the relevant summary statistics. The available data for each contract varies considerable, with roughly 9, 19, 31,

[15] See www.ecx.eu for details.

19 months available for the December 05, 06, 07 and 08 respectively. The first consideration is the relatively small number of observations, which are representative of the number we would observe for relatively infrequently traded stocks on major exchanges (such as the NYSE). The time between consecutive trades varies considerably, with the lowest duration for the December 06 and 08 contracts. As is the norm there is a fair degree of consistency across the instruments for the case of volume.

3.2 Empirical Results

The estimates of the bivariate, duration standardised VAR, represented in equation (1) are reported in table 2-5 for the December 2005, 2006, 2007 and 2008 contract respectively. The results indicate that there is a negative contemporaneous relationship between volume and volatility. Of note is Karpoff (1988) who finds a negative, albeit insignificant, relationship between volume and volatility in the case of financial futures contracts, bonds and commercial paper. There is also some evidence to indicate that lagged volume increases volatility (for the December 2006 and 2007 contract) and so evidence in favour of sequential information arrival. Thus, our results would appear to be inconsistent with the MDH. The volatility is quite persistent, as evidenced by the positive significant coefficients of lagged volatility (there are a number of negative and statistically significant coefficients). For the 2006 and 2008 contracts the contemporaneous interaction term is negative and significant, indicating that trades with longer duration are associated with a lower volatility impact.

In table 6-9, we report the results of the results of the trivariate structural VAR specified in (2). By treating duration as an endogenous variable, we are able to obtain a clearer understanding of the interaction between time, volume and volatility. Our results indicate a level of consistency relative to the duration based bivariate VAR results. Volume continues to have a significantly negative impact on volatility contemporaneously, with some evidence that lagged volume increases volatility. Our results are clearly inconsistent with the MDH. Lagged duration is negative and significant in both the volume and volatility equations signifying that trades with longer durations, are associated with lower volumes and a lower volatility impact. Note current duration has a positive sign in each case...*need to think why.*

In table 10 we report results for the autoregressive coefficients along with their respective t-statistics for all three models. As can be seen all coefficients are statistically significant. Market microstructure theory indicates that market activity increases concomitant to the arrival of unexpected information or clusters of liquidity traders present. Empirical evidence in favour of such a relationship may be indicated by high levels of persistence in the autoregressive coefficients. Consistent with previous studies on a range of different asset classes, the volatility coefficients indicate high levels persistence. The volume coefficients are significantly lower and indicate the difference in the dynamics associated with these instruments. There are similarly low levels of persistence in relation to duration.

4 Conclusions

References

[1] Benz, E. and Hengelbrock, J. (2008), "Liquidity and Price Discovery in the European CO_2 Futures Market: An Intraday Anaysis", *Working Paper*.

[2] Benz, E. and Trück, S. (2009), "Modeling the Price Dynamics of CO_2 Emission Allowances", *Energy Economics*, 31, 2-15.

[3] Convery, F.J. and Redmond, L. (2007), "Market and Price Developments in the European Union Emissions Trading Scheme", *Review of Environmental Economics and Policy* 1, pp. 88-111.

[4] Daskalakis,G., Psychoyios, D., and Markellos, R.N. (2009), "Modeling CO_2 emission allowance prices and derivatives: Evidence from the European trading scheme", forthcoming, *Journal of Banking and Finance*.

[5] Paolella, M.S. and Taschini, L. (2008), "An Econometric Analysis of Emission Trading Allowances", *Journal of Banking and Finance*, 32, 2022-2032.

Table 1: **Summary Statistics for EU ETS Futures**

		Duration		**Volume**		**Volatility(t)**		**Volume(t)**	
Instrument	No. Obs	Mean	Median	Mean	Median	Mean	Median	Mean	Median
Dec. 05	3135	1297.836	421.761	10.318	10	0.229	0.005	0.227	0.019
Dec. 06	15831	599.274	191.000	12.072	10	0.506	0.000	0.367	0.052
Dec. 07	5118	1388.770	392.000	13.216	10	2.695	0.000	0.600	0.026
Dec. 08	5484	750.158	164.000	11.538	10	0.391	0.000	0.709	0.053

Note:

The duration is defined as time elapsed between consecutive trades and is measured in seconds from midnight. Volatility(t) refers to volatility per unit of time and volume(t) represents volume per unit of time.

Table 2: **Structural VAR - Duration based variables (December 2005 Contract)**

This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. The volatility and the volume equations are given as:

$$\begin{aligned} z_{d,t} &= \sum_{i=1}^{p} a_{zi} z_{d,t-i} + \sum_{i=0}^{q} (b_{zi} + c_{zi}\tau_{t-i}) v_{d,t-i} + u_t \\ v_{d,t} &= \sum_{i=1}^{p} a_{vi} z_{d,t-i} + \sum_{i=1}^{q} (b_{vi} + c_{vi}\tau_{t-i}) v_{d,t-i} + \epsilon_t \end{aligned} \quad (8)$$

Estimation is based on the tick-by-tick data for the December 05 EU ETS futures contract on the ECX.

		Volatility Equation		**Volume Equation**	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.185	10.307	-0.017	-2.899
	a_2	0.091	4.975	0.007	1.157
	a_3	0.056	3.066	0.006	0.981
	a_5	0.117	8.391	0.003	0.474
Current volume	b_0	-0.300	-5.257		
Lagged volume	b_1	0.077	1.309	0.207	11.346
	b_2	0.009	0.156	0.084	4.485
	b_3	-0.009	-0.163	0.091	4.857
	b_5	0.041	0.713	0.061	3.233
	b_7	-0.124	-2.102	0.002	0.117
	b_9	-0.009	-0.148	0.061	3.242
Current dur.*volume	c_0	0.013	0.214		
Lagged dur.*volume	c_1	-0.111	-1.852	-0.054	-2.900
	c_3	-0.151	-2.509	-0.022	-1.140

Note:

Table 3: **Structural VAR - Duration based variables (December 2006 Contract)**

This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. The volatility and the volume equations are given as:

$$\begin{aligned} z_{d,t} &= \sum_{i=1}^{p} a_{zi} z_{d,t-i} + \sum_{i=0}^{q} (b_{zi} + c_{zi}\tau_{t-i}) v_{d,t-i} + u_t \\ v_{d,t} &= \sum_{i=1}^{p} a_{vi} z_{d,t-i} + \sum_{i=1}^{q} (b_{vi} + c_{vi}\tau_{t-i}) v_{d,t-i} + \epsilon_t \end{aligned} \tag{9}$$

Estimation is based on the tick-by-tick data for the December 06 EU ETS futures contract on the ECX.

		Volatility Equation		**Volume Equation**	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.168	21.121	-0.002	-1.511
	a_2	0.057	7.071	0.002	1.038
	a_3	0.061	7.563	0.001	0.610
	a_4	0.063	7.719	0.003	1.759
	a_5	0.020	2.477	0.003	1.812
	a_6	0.060	7.335	0.002	0.927
	a_7	0.022	2.796	0.001	0.469
	a_8	0.053	6.547	-0.001	-0.863
	a_9	0.017	2.073	0.000	0.352
Current volume	b_0	-0.304	-7.788		
Lagged volume	b_1	0.072	1.811	0.174	21.765
	b_2	-0.043	-1.074	0.088	10.814
	b_3	0.028	0.705	0.053	6.503
	b_4	0.099	2.470	0.030	3.703
	b_5	0.043	1.086	0.032	3.938
	b_6	-0.010	-0.164	0.029	3.511
	b_7	0.025	0.637	0.043	5.306
	b_8	-0.012	-0.298	0.031	3.760
	b_9	0.001	0.018	0.019	2.315
Current dur.*volume	c_0	-0.233	-6.470		
Lagged dur.*volume	c_1	0.049	1.340	-0.040	-5.473

Note:

Table 4: **Structural VAR - Duration based variables (December 2007 Contract)**

This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. The volatility and the volume equations are given as:

$$z_{d,t} = \sum_{i=1}^{p} a_{zi} z_{d,t-i} + \sum_{i=0}^{q} (b_{zi} + c_{zi}\tau_{t-i}) v_{d,t-i} + u_t \quad (10)$$

$$v_{d,t} = \sum_{i=1}^{p} a_{vi} z_{d,t-i} + \sum_{i=1}^{q} (b_{vi} + c_{vi}\tau_{t-i}) v_{d,t-i} + \epsilon_t$$

Estimation is based on the tick-by-tick data for the December 07 EU ETS futures contract on the ECX.

		Volatility Equation		**Volume Equation**	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.349	25.517	-0.006	-2.100
	a_2	-0.068	-4.650	0.006	2.040
	a_3	0.051	3.455	-0.007	-2.343
	a_4	-0.023	-1.548	0.008	2.748
	a_5	0.037	2.540	0.007	2.388
	a_6	0.034	2.283	0.001	0.312
	a_8	0.039	2.624	0.002	0.627
	a_{10}	0.033	2.255	-0.004	-1.259
	a_{13}	0.056	3.829	-0.004	-1.453
	a_{14}	-0.033	-2.272	0.004	1.394
	a_{15}	0.034	2.328	-0.001	-0.506
	a_{18}	0.038	2.583	0.000	0.054
Current volume	b_0	-0.293	-4.233		
Lagged volume	b_1	0.094	1.324	0.222	15.705
	b_2	-0.026	-0.368	0.086	5.947
	b_3	0.104	1.460	0.049	3.372
	b_5	0.149	2.089	0.043	2.930
	b_9	0.154	2.154	0.007	0.472
	b_{11}	-0.083	-1.162	0.035	2.404
Current dur.*volume	c_0	-0.095	-1.528		
Lagged dur.*volume	c_1	-0.143	-2.236	-0.054	-4.245
	c_4	-0.163	-2.546	0.031	2.358
	c_5	0.143	2.233	-0.006	-0.471
	c_9	-0.191	-2.966	-0.033	-2.534

Note:

Table 5: **Structural VAR - Duration based variables (December 2008 Contract)**

This table reports the results of the bivariate volume-volatility VAR. The variables are standardized with respect to duration and are in log-form to ensure that they remain positive. The volatility and the volume equations are given as:

$$\begin{aligned} z_{d,t} &= \sum_{i=1}^{p} a_{zi} z_{d,t-i} + \sum_{i=0}^{q} (b_{zi} + c_{zi}\tau_{t-i}) v_{d,t-i} + u_t \\ v_{d,t} &= \sum_{i=1}^{p} a_{vi} z_{d,t-i} + \sum_{i=1}^{q} (b_{vi} + c_{vi}\tau_{t-i}) v_{d,t-i} + \epsilon_t \end{aligned} \quad (11)$$

Estimation is based on the tick-by-tick data for the December 08 EU ETS futures contract on the ECX.

		Volatility Equation		**Volume Equation**	
		Coefficient	t-stats	Coefficient	t-stats
Lagged volatility	a_1	0.125	9.248	-0.011	-2.427
	a_2	0.059	4.290	-0.001	-0.147
	a_3	0.064	4.712	-0.003	-0.752
	a_4	-0.032	-2.326	0.002	0.374
	a_5	0.033	2.446	-0.003	-0.642
	a_7	0.039	2.858	0.005	1.063
	a_9	0.037	2.731	0.005	1.071
	a_{10}	0.037	2.724	0.011	2.486
Current volume	b_0	-0.326	-7.856		
Lagged volume	b_1	0.033	0.779	0.233	17.122
	b_2	-0.038	-0.892	0.107	7.628
	b_3	-0.067	-1.555	0.078	5.500
Current dur.*volume	c_0	-0.016	-4.231		
Lagged dur.*volume	c_1	-0.043	-1.106	-0.075	-6.095
	c_3	0.013	0.331	0.026	2.029

Note:

Table 6: **Structural VAR (December 2005 Contract)**

This table reports the results of the trivariate duration volume volatility VAR. The variables are in log form to ensure that they remain positive. The respective duration, volatility and the volume equations are:

$$\begin{aligned} d_t &= \sum_{i=1}^{p1} \gamma_i d_{t-i} + \sum_{i=1}^{q1} \rho_i V_{t-i} + \sum_{i=1}^{r1} \delta_i Z_{t-i} + \varepsilon_t \\ V_t &= \sum_{i=0}^{p2} \lambda_i d_{t-i} + \sum_{i=1}^{q2} \zeta_i V_{t-i} + \sum_{i=0}^{r2} \phi_i Z_{t-i} + \eta_t \\ Z_t &= \sum_{i=0}^{p3} \beta_i d_{t-i} + \sum_{i=0}^{q3} \theta_i V_{t-i} + \sum_{i=1}^{r3} \alpha_i Z_{t-i} + \zeta_t \end{aligned} \quad (12)$$

Estimation is based on the tick-by-tick data for the December 05 EU ETS futures contract on the ECX.

		Duration Equation		**Volume Equation**		**Volatility Equation**	
		Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
Current duration	γ_0					1.335	15.361
Lagged duration	γ_1	0.218	11.729			-0.362	-3.361
	γ_2	0.096	5.030				
	γ_3	0.058	3.059			-0.238	-2.565
	γ_4	0.048	2.498				
	γ_5	0.065	3.393			-0.268	-2.882
	γ_7			0.046	2.141		
Current volume	ρ_0					-0.277	-3.681
Lagged volume	ρ_1			0.178	9.917		
	ρ_2			0.040	2.185		
	ρ_3			0.052	2.879	-0.206	-2.702
	ρ_5			0.054	2.989		
	ρ_7			0.036	2.030	-0.165	-2.192
Current volatility	δ_0			-0.016	-3.681		
Lagged volatility	δ_1			-0.011	-2.550	0.201	11.197
	δ_2					0.098	5.341
	δ_3					0.065	3.561
	δ_5					0.129	7.062
	δ_7			-0.010	-2.265		

Note:

Table 7: **Structural VAR (December 2006 Contract)**

This table reports the results of the trivariate duration volume volatility VAR. The variables are in log form to ensure that they remain positive. The respective duration, volatility and the volume equations are:

$$\begin{aligned} d_t &= \sum_{i=1}^{p1} \gamma_i d_{t-i} + \sum_{i=1}^{q1} \rho_i V_{t-i} + \sum_{i=1}^{r1} \delta_i Z_{t-i} + \varepsilon_t \\ V_t &= \sum_{i=0}^{p2} \lambda_i d_{t-i} + \sum_{i=1}^{q2} \zeta_i V_{t-i} + \sum_{i=0}^{r2} \phi_i Z_{t-i} + \eta_t \\ Z_t &= \sum_{i=0}^{p3} \beta_i d_{t-i} + \sum_{i=0}^{q3} \theta_i V_{t-i} + \sum_{i=1}^{r3} \alpha_i Z_{t-i} + \zeta_t \end{aligned} \quad (13)$$

Estimation is based on the tick-by-tick data for the December 06 EU ETS futures contract on the ECX.

		Duration Equation		**Volume Equation**		**Volatility Equation**	
		Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
Current duration	γ_0			0.050	6.515	1.145	21.567
Lagged duration	γ_1	0.220	27.217			-0.208	-3.769
	γ_2	0.095	11.484				
	γ_3	0.053	6.328				
	γ_4	0.019	2.272	-0.027	-3.442	-0.233	-4.203
	γ_5	0.031	3.718				
	γ_6	0.020	2.434				
	γ_7	0.032	3.829				
	γ_8	0.020	2.445				
	γ_9	0.018	2.134				
Current volume	ρ_0	0.046	5.533			-0.487	-8.808
Lagged volume	ρ_1			0.175	21.989	0.122	2.166
	ρ_2			0.077	9.485		
	ρ_3			0.059	7.235		
	ρ_4			0.033	4.048		
	ρ_5			0.031	3.864		
	ρ_6	-0.018	-2.071	0.023	2.830		
	ρ_7			0.037	4.601		
	ρ_8			0.027	3.357		
Current volatility	δ_0			-0.010	-8.808		
Lagged volatility	δ_1					0.201	11.197
	δ_2	-0.004	-3.163			0.098	5.341
	δ_3	-0.003	-2.289			0.065	3.561
	δ_4			0.003	2.289		
	δ_5	-0.003	-2.696			0.129	7.062
	δ_6						
	δ_7	-0.003	-2.151				
	δ_8						
	δ_9						

Note:

Table 8: **Structural VAR (December 2007 Contract)**

This table reports the results of the trivariate duration volume volatility VAR. The variables are in log form to ensure that they remain positive. The respective duration, volatility and the volume equations are:

$$\begin{aligned} d_t &= \sum_{i=1}^{p1} \gamma_i d_{t-i} + \sum_{i=1}^{q1} \rho_i V_{t-i} + \sum_{i=1}^{r1} \delta_i Z_{t-i} + \varepsilon_t \\ V_t &= \sum_{i=0}^{p2} \lambda_i d_{t-i} + \sum_{i=1}^{q2} \zeta_i V_{t-i} + \sum_{i=0}^{r2} \phi_i Z_{t-i} + \eta_t \\ Z_t &= \sum_{i=0}^{p3} \beta_i d_{t-i} + \sum_{i=0}^{q3} \theta_i V_{t-i} + \sum_{i=1}^{r3} \alpha_i Z_{t-i} + \zeta_t \end{aligned} \tag{14}$$

Estimation is based on the tick-by-tick data for the December 07 EU ETS futures contract on the ECX.

		Duration Equation		**Volume Equation**		**Volatility Equation**	
		Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
Current duration	γ_0			0.109	7.669	1.252	13.459
Lagged duration	γ_1	0.275	19.090			-0.562	-5.748
	γ_2	0.901	6.076				
	γ_3	0.064	4.250				
	γ_5	0.036	2.414				
	γ_9					-0.364	-3.689
Current volume	ρ_0	0.043	3.061			-0.336	-3.605
Lagged volume	ρ_1			0.223	15.798		
	ρ_2			0.087	6.019		
	ρ_3			0.040	2.780	0.214	2.230
	ρ_4			0.030	2.030	-0.227	-2.360
	ρ_5					0.320	3.330
	ρ_6			0.030	2.000		
	ρ_9			-0.032	-2.226		
Current volatility	δ_0			-0.008	-3.605		
Lagged volatility	δ_1					0.350	25.590
	δ_2	-0.006	-2.538			-0.069	-4.711
	δ_3			-0.007	-3.269	0.051	3.488
	δ_4			0.005	2.102		
	δ_5			0.005	2.177	0.036	2.439
	δ_6					0.035	2.399
	δ_8					0.038	2.611

Note:

Table 9: **Structural VAR (December 2008 Contract)**

This table reports the results of the trivariate duration volume volatility VAR. The variables are in log form to ensure that they remain positive. The respective duration, volatility and the volume equations are:

$$
\begin{aligned}
d_t &= \sum_{i=1}^{p1} \gamma_i d_{t-i} + \sum_{i=1}^{q1} \rho_i V_{t-i} + \sum_{i=1}^{r1} \delta_i Z_{t-i} + \varepsilon_t \\
V_t &= \sum_{i=0}^{p2} \lambda_i d_{t-i} + \sum_{i=1}^{q2} \zeta_i V_{t-i} + \sum_{i=0}^{r2} \phi_i Z_{t-i} + \eta_t \\
Z_t &= \sum_{i=0}^{p3} \beta_i d_{t-i} + \sum_{i=0}^{q3} \theta_i V_{t-i} + \sum_{i=1}^{r3} \alpha_i Z_{t-i} + \zeta_t
\end{aligned} \quad (15)
$$

Estimation is based on the tick-by-tick data for the December 08 EU ETS futures contract on the ECX.

		Duration Equation		**Volume Equation**		**Volatility Equation**	
		Coefficient	t-stats	Coefficient	t-stats	Coefficient	t-stats
Current duration	γ_0			0.069	5.099	1.189	21.015
Lagged duration	γ_1	0.314	22.246			-0.221	-3.604
	γ_2	0.094	6.402				
	γ_3						
	γ_5	0.042	2.863				
	γ_7	0.033	2.787				
	γ_9	0.033	2.229				
Current volume	ρ_0					-0.467	-8.001
Lagged volume	ρ_1			0.183	13.523		
	ρ_2			0.120	8.757		
	ρ_3			0.111	7.987		
	ρ_6			0.037	2.674		
	ρ_7			0.029	2.049		
	ρ_9	-0.029	-2.047				
Current volatility	δ_0			-0.025	-8.001		
Lagged volatility	δ_1					0.126	9.300
	δ_2					0.059	4.329
	δ_3					0.065	4.734
	δ_4					-0.031	-2.258
	δ_5					0.034	2.502
	δ_7					0.039	2.870
	δ_9					0.038	2.786

Note:

Table 10: **Autoregressive coefficients (β) (December 2005-2008 Contracts)**

This table reports the Autoregressive coefficients (β) for Duration, Volume and Trade Variance models:

$$
\begin{aligned}
d_t &= \psi_t \epsilon_t \quad \epsilon_t \sim i.i.d.(1, \sigma_\epsilon^2) \\
\psi_t &= \omega + \alpha d_{t-1} + \beta \psi_{t-1}
\end{aligned}
\tag{16}
$$

$$
\begin{aligned}
v_t &= \phi_t \eta_t, \quad \eta_t \sim i.i.d.(1, \sigma_\eta^2) \\
\phi_t &= \omega + \alpha v_{t-1} + \beta \phi_{t-1}
\end{aligned}
\tag{17}
$$

$$
\begin{aligned}
y_t &= \sigma_t \zeta_t, \quad \zeta_t \sim i.i.d.(0, 1) \\
\sigma_t^2 &= \omega + \alpha y_{t-1}^2 + \beta \sigma_{t-1}^2
\end{aligned}
\tag{18}
$$

Estimation is based on the tick-by-tick data for the December 05-08 EU ETS futures contract on the ECX.

EU ETS futures contract	**ACD**	**ACV**	**GARCH**
December 2005	0.644	0.803	0.950
	(24.258)	(11.025)	(192.602)
December 2006	0.696	0.750	0.968
	(15.039)	(16.266)	(594.44)
December 2007	0.559	0.481	0.929
	(6.976)	(5.338)	(244.370)
December 2008	0.397	0.709	0.962
	(6.221)	(13.074)	(299.223)

Note: