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The Information Content in Bond Model Residuals : An Empirical Study on the Belgian Bond Market

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Abstract. We estimate daily Vasicek, CIR, and spline models on Belgian data and compare the trading profits that can be made on the basis of the model residuals. Abnormal returns are negatively related to lagged mispricing. Contrarian strategies—buying underpriced bonds, and especially selling overpriced bonds—yield significant abnormal returns even when the trade is delayed by up to five days after observing the mispricing. The spline model seems to overfit the data and is least able to detect mispricing. Large model residuals are more likely to be the result of model misspecification or -estimation than are small or medium-sized residuals.

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Key Words: Bonds, One-Factor Model, Spline, Duration, Market Efficiency

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Abstract. We estimate daily Vasicek, CIR, and spline models on Belgian data and compare the trading profits that can be made on the basis of the model residuals. Abnormal returns are negatively related to lagged mispricing. Contrarian strategies—buying underpriced bonds, and especially selling overpriced bonds—yield significant abnormal returns even when the trade is delayed by up to five days after observing the mispricing. The spline model seems to overfit the data and is least able to detect mispricing. Large model residuals are more likely to be the result of model misspecification or -estimation than are small or medium-sized residuals.

Introduction

Within the class of one-state-variable term structure models in continuous time, the models by Vasicek (1977) and Cox-Ingersoll-Ross (CIR) (1985b), having tractable closed-form solutions based on a stationary process for the short-term interest rate, are among the most popular. The nature of empirical work on these models (and of more recent competitors) depends on one's objective and selection criterion. First, one could test competing term structure models on purely statistical grounds. For example, Brown and Dybvig (1985) estimate the CIR model on monthly price quotes for U.S. Treasury issues from 1952 through 1983, and De Munnik and Schotman (1994) test both the Vasicek model and the CIR model with daily data of Dutch Treasury bonds from 1990 through 1991. Related tests on real return data are provided by Gibbons and Ramaswamy (1993), Brown and Schaefer (1994), Pearson and Sun (1994). Alternatively, the models can be compared on economic rather than statistical grounds. For instance, one could evaluate their comparative performance as predictors of future interest rates and inflation (see Fama (1990)). Or one could test whether the estimated term structure models contain information about future bond returns, a selection criterion which should appeal to bond traders or financial analysts. In this paper we adopt the latter criterion to compare the merits of the Vasicek and CIR models relative to each other and to the simpler cubic spline model. Thus, every day we estimate all three models on cross-sectional data of Belgian treasury bonds and interbank deposits from 1991 through 1992. We then test whether one can realize abnormal returns by buying (shortselling) bonds that, on that day, were classified as undervalued (overvalued) relative to a particular estimated term structure model. Unlike Pearson and Sun (1994) and De Munnik and Schotman (1994), we estimate the Vasicek and CIR yield curve models on a day-to-day cross-sectional basis, without any pooling over time or without any inter-temporal constraints on the parameters that were assumed to be constant over time in the derivation of the equilibrium pricing model. In this sense, our approach is similar to standard practice among option traders, who re-estimate volatilities every day or use implicit standard deviations as a basis for trading although their pricing model assumes constant volatilities. Our day-to-day approach also has the merit that it does not load the dice in favor of the cubic spline model, where intertemporal constraints are never imposed.

The structure and findings of the paper are as follows. Part I deals with the estimation of term structure models. We start with a brief review of the basics of term structure models in general and the Vasicek and CIR models in particular, and then present and discuss the estimates obtained from our sample. Part II tests whether the residuals from the estimated term structure model contain any information that would be useful for a trader. We follow two approaches. First we regress abnormal holding period returns from an individual bond on the previous trading day's term structure model residual (that is, actual price minus model price). Second, we compute abnormal returns from various trading rules based on differences between observed and model prices. In each of these tests, abnormal returns from bond trading are measured relative to three alternative benchmarks. One benchmark is the return on the bonds that would have been observed if prices would, at all times, perfectly fit the term structure model that was used to identify the mispricing. Our second benchmark is the contemporaneous realized return on a well-diversified portfolio with the same duration as the bond(s) selected by the trading rule, while the third benchmark also matches the traded bonds in terms of convexity. Both the regression tests and the results from the trading rule reveal that model residuals are economically useful. In addition, the trading results based on the two economic models are superior to the results obtained when the decisions to buy or sell are based on the simple cubic spline.

I. Estimation of the Bond Pricing Models

Section I.1 briefly presents the Vasicek, CIR and spline models. Section I.2 describes the data and presents the estimation method for our cross-sectional estimation on coupon bond prices. The empirical results are discussed in Sections I.3.

I.1 Three Bond Pricing Models

Let P(r, t) denote the price of a zero-coupon bond or pure discount bond at t and assume that the underlying variable, the short term interest rate r(t), follows a diffusion process which is continuous over time and exhibits no jumps:

$$dr = \gamma(r,t)dt + \sigma(r,t)dz \, , \qquad (1)$$

where

dr is the change in the short term interest rate r(t);

$\gamma(r,t)$ is the drift rate of r(t); γ may depend both on r(t) and t;

$\sigma(r,t)$ is the standard deviation of changes in r(t); σ may depend both on r(t) and t;

dz is the standard Wiener process with zero mean zero unit *per annum* variance.

The familiar Black-Scholes (1973), Merton (1973) no-arbitrage equation is

$$\frac{\partial P}{\partial t} + \frac{\partial P}{\partial r}\,[\gamma(r, t) - \lambda(r, t)\,\sigma(r, t)] + \frac{1}{2}\,\frac{\partial^2 P}{\partial r^2}\,\sigma^2(r, t) - r(t)\,P = 0\,. \tag{2}$$

In this expression, $\lambda(r, t)$ is the price of interest risk at time t, and the factor $[\gamma(r, t) - \lambda(r, t)\,\sigma(r, t)]$ is the risk-adjusted drift rate of the underlying state variable, *in casu* the short term interest rate in equation (2).

In Vasicek (1977), the instant interest rate follows a mean-reverting normal (Ornstein-Uhlenbeck) process,

$$dr = \kappa\,(m - r)\,dt + \sigma\,dz\ , \tag{3}$$

where κ, m and σ are constants and dz is a Wiener process. With (3), the fundamental differential equation in (2) becomes

$$\frac{\partial P}{\partial t} + \frac{\partial P}{\partial r}\,[\kappa\,(m - r) - \lambda(r, t)\,\sigma(r, t)] + \frac{1}{2}\,\frac{\partial^2 P}{\partial r^2}\,\sigma^2 - r(t)\,P = 0\,. \tag{4}$$

Recall that $P_T(r, t)$ is the price, at t, of a zero-coupon bond or discount bond maturing at T and contingent on the short term interest rate r(t). By assuming a constant market price of risk λ over time and using the boundary condition that, at maturity, $P_T(r,T)$ equals unity, the following closed form pricing model is obtained:

$$P_T(r, t) = \exp\left\{-\phi_0\{1 - e^{-\kappa(T-t)}\} + \phi_1\{1 - \kappa(T-t) - e^{-\kappa(T-t)}\} - \phi_2\{1 - e^{-\kappa(T-t)}\}^2\right\}, \tag{5}$$

where

$$\phi_0 = \frac{r}{\kappa}, \tag{6}$$

$$\phi_1 = \frac{\kappa\,m - \lambda\,\sigma}{\kappa^2} - \frac{1}{2}\,\frac{\sigma^2}{\kappa^3}, \tag{7}$$

and

$$\phi_2 = \frac{1}{4}\,\frac{\sigma^2}{\kappa^3}\,. \tag{8}$$

If the short term rate r(t) is taken to be unobservable, there are four coefficients to be estimated: κ, ϕ_0, ϕ_1 and ϕ_2. From these estimated coefficients we can derive the implied parameters,

implied short-term rate: $r = \kappa\,\phi_0\,,$ (9)

yield on a bond with $T \to \infty$: $R_L = \kappa\,\phi_1\,,$ (10)

implied variance of dr $\sigma^2 = 4\,\kappa^3\phi_2\,,$ (11)

risk-adjusted drift of r: $\mu \equiv \kappa\,(m-r) - \lambda\,\sigma = (\phi_1 + 2\phi_2)\kappa^2 - \kappa\,r\,.$ (12)

In contrast, Cox, Ingersoll and Ross (1985b) adopt a specific general-equilibrium approach that allows them to derive both the interest rate dynamics and the corresponding price of risk:

$$dr = \kappa\,(m - r)\,dt + \sigma\sqrt{r}\,dz\,, \tag{13}$$

$$\lambda(r, t) = \frac{q}{\sigma}\sqrt{r(t)}\,, \tag{14}$$

where q is a constant. As a result, the general differential equation (2) can be specified as

$$\frac{\partial P}{\partial t} + \frac{\partial P}{\partial r}\,[\kappa\,(m - r) - q\,r(t)\,] + \frac{1}{2}\frac{\partial^2 P}{\partial r^2}\,\sigma^2(r, t) - r(t)\,P = 0\,. \tag{15}$$

With the boundary condition $P_T(r,T)=1$ for a maturing discount bond, the solution to equation (15) takes the following specific form:

$$P_T(r, t) = \left[\frac{\theta_1\, e^{\theta_2(T-t)}}{\theta_2\, e^{\theta_2(T-t)} - 1 + \theta_1}\right]^{\theta_3} \exp\left\{\frac{-r\, e^{\theta_1(T-t)} - 1}{\theta_2\, e^{\theta_2(T-t)} - 1 + \theta_1}\right\}, \tag{16}$$

where

$$\theta_1 = \sqrt{(\kappa + 1)^2 + 2\sigma^2}\,, \tag{17}$$

$$\theta_2 = (\kappa + q + \theta_1)/2\,, \tag{18}$$

and

$$\theta_3 = 2\kappa m/\sigma^2\,. \tag{19}$$

Also in this model there are four coefficients to be estimated: r, θ_1, θ_2 and θ_3. From these estimated coefficients we can derive the implied parameters,

yield on a bond with $T\rightarrow\infty$: $$R_L = \theta_3\,(\theta_1 - \theta_2)\,, \tag{20}$$

implied variance of dr: $$\sigma^2\,r = 2\theta_2\,(\theta_1 - \theta_2)\,r\,, \tag{21}$$

risk-adjusted drift or r: $$\mu = \kappa\,(m-r) - q\,r(t) = \theta_3\,\sigma^2/2 - (2\theta_2 - \theta_1)\,r(t)\,. \tag{22}$$

The cubic spline model, finally, is a purely descriptive model without economic foundations. The term structure function consists of a concatenation of (in our case) three third-degree polynomials—depending on whether the time to maturity is below s_1, between s_1 and s_2, or above s_2. In addition, at the knot points $T=s_1$ (set at 2 years) and $T=s_2$ (set at 4 years) there must be continuity in the levels and first and second derivatives. This is achieved by setting

$$P_T(r, t) = 1 + aT + bT^2 + cT^3 + d\,\{Max(T-s_1,0)\}^3 + e\,\{Max(T-s_1,0)\}^3\,. \tag{23}$$

I.2. Data and Methodology

The competing models in (5), (16), and (23) were estimated from data on BEF interbank deposits and BEF 'linear' bonds (*Obligations Linéaires/Lineaire Obligaties*, or OLOs). In this section we describe the data and the estimation procedure.

I.2.1. Bond Prices and Bank Deposit Data

Like France's *Obligations Assimilables*, OLO bonds are floated in consecutive tranches rather than in one single issue. Each new tranche of a given 'line' has identical terms and conditions and is fully fungible (*assimilable*) with earlier tranche issues of the same line. The number of outstanding OLOs is much smaller than the number of ordinary government bonds traded during the same period. However, for the purpose of testing bond pricing models, OLOs have many advantages relative to ordinary bonds. First, OLOs are registered bonds. In contrast, the ordinary government bonds are bearer securities, which are more expensive to trade. Second, because OLOs are registered, they are mainly held by corporations. Because of this, tax clientèle effects are less likely to be a problem for OLOs than for ordinary bonds, which can be held by individuals as well.[1] Third, the coupons from OLOs are not subject to any withholding tax. This makes OLOs more convenient to corporations than ordinary bonds. Fourth, OLOs are more actively traded than ordinary bonds, partly because the primary dealers make a market. In contrast, ordinary bonds are traded either during a (low-volume) daily call auction on the Brussels Exchange, or off the exchange. Finally, OLOs are straight bonds with maturities of up to twenty years, while ordinary bonds are more short-lived and tend to have put or call option features.

Daily OLO price data and BEF Brussels interbank offer rates (BIBOR), from March 27, 1991 through December 30, 1992, were obtained from the *Financieel Economische Tijd* (FET) data service. After deleting non-trading days and some thin-trading days, 421 daily cross-section samples are available. At the beginning of our sample period we have six outstanding OLOs, with times to maturity ranging from about three to twelve years, while at the end we have twelve OLOs with times to maturity ranging from about one to twenty years (Table 1).

The OLO price data reported by the FET are last-trade transaction prices, which implies that they contain bid-ask noise. The maximum allowed bid-ask spread is 25 basis points. Bond

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[1]Under personal taxation, interest income on ordinary bonds is subject to a withholding tax of 10% plus, possibly, a (widely evaded) progeressive additional tax if worldwide interest income exceeds certain thresholds. Capital gains go untaxed. Corporations, in contrast, all pay the same tax on interest income and capital gains.

price quotes have to be grossed up with accrued interest to obtain the effective invoice price. In addition, bond prices have to be corrected for the one-week settlement effect. That is, the invoice price is actually a one-week forward price. Thus, the bond prices we use for estimation are obtained from the invoice price as follows:

$$P_T = \frac{\text{quote + accrued interest}}{1 + (7/365)\ \text{BIBOR 1 month}}. \tag{24}$$

We use the 1-month BIBOR because the one-week interest rate is not available to us. Note that while accrued interest on bonds is based on a 360-day year, the Brussels interbank market uses a 365-day year to calculate interest; this explains the factor (7/365) in the numerator.

To represent the short end of the maturity spectrum we have preferred interbank deposits over treasury bills. It is true that there has been an organized secondary market for treasury bills as of the spring of 1991, which is also the beginning of our sample; however, the T-bill data for the first trading year are rather suspect because T-bill yields often exceeded BIBOR rate by up to 10 basis points. This unexpected premium relative to BIBOR reflected the extreme thinness of the market in the first year of trading. In contrast, the interbank money market is very deep, and has bid-ask spreads of 12.5 basis points *per annum* except during periods of EMS tensions.

Interbank interest rate data from the *Financieel Economische Tijd* bear on maturities of 1, 2, 3, 6, or 12 months (Table 2). To obtain midpoint prices for short-term discount bond from the BIBOR data, we converted offer rates into mean interbank rates by subtracting half the bid-ask spread and then discounting:

$$P_T = \frac{100}{1 + (T-t) \times [\text{BIBOR}(t,T) - 6.25 \text{ points}]}, \tag{25}$$

where, following the convention in the BEF interbank market, T is computed using the actual number of days and a 365-day year. With six to twelve OLOs and five interbank deposits, each cross-section contains eleven to seventeen assets.[2]

I.2.2. Estimation

The pricing equations (5), (16), and (23) refer to zero-coupon bonds, but OLOs are coupon bonds, that is, portfolios of different default-free discount bonds. Thus, the valuation formula for a coupon bond takes the following form:

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[2] When a bond was not traded on a particular day, we dropped the bond from the sample, so that the actual number of observations is sometimes smaller than the number of outstanding bonds.

$$P_T(r, t; c, N) = \sum_{j=1}^{N} CF_j \, P_{T_j}(r, t) \, , \tag{26}$$

where

$P_T(r, t; c, N)$ is the effective price (quoted price plus accrued interest) of a coupon bond with N annual coupons c and time to maturity T;

N is the number of times cash flows will occur during the remaining life of the coupon bond.

CF_j is the cashflow (c or 100+c) received at times T_j, j=1,...N;

$P_{T_j}(r, t)$ is the price of a discount bond with time to maturity T_j as given by equation (5) (Vasicek), (16) (CIR), or (23) (spline).

For the economic models we use non-linear least-squares to estimate (26), assuming, like Brown and Dybvig(1986) and De Munnik and Schotman (1992), that empirical bond prices have homoskedastic errors across maturities. Because our daily cross-sectional samples have at most seventeen data points and we did not want to pool over time (for reasons discussed in the introduction), GMM was deemed unsuitable. For the spline model we used OLS.

I.3. Discussion of the Empirical Results

As shown in Figure 1, during most of the sample period the term structure was characterized by either a steep decline or a positive hump situated around four months to maturity.[3] In contrast, during the last 70 trading days following September 16, 1992—a period characterized by heavy tensions within the EMS and very high short-term interest rates—, both the spline and the Vasicek estimates came up with a negative hump. For these last 70 days, the CIR model estimates did not converge at all, while the Vasicek model was able to fit the negative hump only by allowing the implied σ^2 to be negative.[4] Because negative variance do not make sense and because we want to compare the results from trading on the basis of all three models (Vasicek, CIR, and cubic splines), our discussion will focus on the first 351 trading days. For completeness, we nevertheless also provide the results for both the last subperiod and the entire 421-day sample.

[3]Although it is known that the CIR model can produce a humped term structure, such a shape has not been observed by Brown and Dybvig (1985) or De Munnik and Schotman (1992).

[4]Hull (1993) argues that, for an interest contingent claim, λ is likely to be negative. The alternative explanation, a negative σ, does not make any sense at all; however, Brown and Dybvig (1988) obtain some negative estimates for the CIR variance.

Table 3 presents mean values, maxima, and minima of the estimated and implied parameters for the Vasicek model (Panel A) and the CIR model (Panel B). We first discuss the estimations from a statistical point of view, and then the implied parameters and their economic content.

During the first (351-day) period—see panel (A), first period for the Vasicek model; panel (B) for the CIR model; panel (C), first period for the spline model—the CIR model marginally outperforms the Vasicek model in terms of goodness-of-fit: the average of root mean square error (RMSE) of the regression is somewhat smaller for the CIR model (12.4 basis points for a bond with par value 100) than the Vasicek model (13.5 basis points). This RMSE is roughly equal to the maximum one would expect from a purely random bid-ask bounce: with a maximum bid-ask spread of at most 25 basis points and equal marginal probabilities that the price is a bid or ask price, the bid-ask bounce generates a RMSE of, at most, $\sqrt{(0.5)^2 \times (0.0025)^2}$ = 12.5 basis points. We will provide evidence, below, that the residual RMSE is not just random bid-ask bounce, though; that is, the actual spreads must, on average, have been below the legal maximum of 25 basis points. While the residual RMSE produced by the two economic models is low relative to the maximal bid-ask bounce and relative to the results obtained by De Munnik and Schotman (1994),[5] the cubic spline easily beats the other two models in this respect: its mean RMSE is a mere 0.08 basis points. This lower RMSE suggests that the actual bid-ask spread probably was below the legal maximum 25 basis points—otherwise it would be hard to explain RMSEs below 12.5 basis points. However, the trading rule results presented in Section II will demonstrate that the spline's low residual RMSE also reflects the spline's tendency to over-fit.

We now discuss the economic content of the estimates, focusing on the derived parameters presented in the right hand parts of Table 3. There is substantial agreement between the two economic models—Vasicek and CIR—with respect to the estimated instantaneous interest rate and the implied long-term yield. The implied instantaneous interest rate in the Vasicek model is, on average, 8.76%, while in the CIR model the mean instantaneous interest rate is (directly) estimated at 8.90%, on average. These are not unreasonable orders of magnitude. For instance, the mean 1-month BIBOR, which is the closest we can get to the (unobservable) instantaneous rate, has a mean of 9.4% p.a., as can be seen from Table 2. With

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[5]De Munnik and Schotman (1992) found an average standard error of 18 basis points for the Dutch market. The difference between their and our results is unlikely to be explained by a higher turbulence during the Dutch sample period: while the yield curves obtained by De Munnik and Schotman are almost flat, we have steeply declining and humped curves. The higher standard deviations in De Munnik and Schotman are more likely to be the result of pooling data over one week, something we did not do. During the last 70 days in our sample, however, the residual standard deviations seem to have been substantially higher in both the spline and Vasicek models.

respect to the implied long bond yield, R_L, the Vasicek model produces a mean estimate of 8.54%, which is very close to the mean long-term rate of 8.52% in the CIR model. There is less of a consensus, however, between the two models with respect to the risk-adjusted drift in the short-term rate and the standard deviation of r. In the Vasicek model the annualized risk adjusted drift rate of the short term interest rate, $\mu = \kappa(m-r) - \lambda\sigma$, has a mean of 0.035%, while the CIR counterpart, $\kappa(m-r) - \lambda(r, t)\,\sigma\sqrt{r}$, equals 0.019%. The estimated *per annum* standard deviation of dr is, on average, 5%. From the estimates of $\sigma\sqrt{r}$, the corresponding CIR average standard deviation is 3.38%. The last parameter, κ, represents the speed of reversion of the short-term rate r towards its unconditional expectation, m. Estimates of this parameter can only be extracted for the Vasicek model. These estimates are invariably positive, ranging between 0.004 and 0.024 per day with a mean of 0.001 per day. This is approximately one-half of the estimate obtained from the time series of daily one-month BIBOR interest rates.[6]

We have already compared the average errors of the cross-sectional regressions across models. Deviations between actual prices and model prices can also be analyzed longitudinally, i.e. per asset rather than per cross-section, so as to verify whether or not the model consistently misprices some individual bonds. Bond pricing errors or model residuals for individual bonds are analyzed in depth in Part II; so at this stage we merely discuss the mean error and the mean absolute error (MAE) per asset, as reported in Table 4 and Figure 2. We initially focus on the results for the 351-day sample, presented towards the end of Table 4, where we have estimates for all three models.

Mean errors exhibit no clear pattern across assets, but the mean absolute errors (MAE) are more revealing. In both models the MAEs tends to be smaller for interbank deposits than for bonds, with figures well below ten basis points and increasing with time to maturity. The MAEs of OLO lines 03, 07, and 09 exceed ten basis points (Figures 2.A.2 and 2.B.2); in addition, for OLO03 and 09 the size of the MAE is also close to the size of the mean error, which means that virtually all of the errors have the same sign—negative for OLO03, and positive for OLO09. None of the traders we talked to has provided any reason why these lines would behave abnormally.[7] Moreover, the pricing errors obtained for OLO03/09 from the spline functions are less consistently of the same sign and much smaller in absolute value than the errors obtained from the two economic models (Figures 2.A.2 and 2.B.2). In order not to

[6]The time series results are not tabulated here. The time series estimates of the daily mean-reversion parameter in a time series of one-month interest rates are around 0.02, consistent with empirical evidence of very high autocorrelation in the short interest rates. The implied value for κ is also 0.02, because the mean reversion parameter in discrete-time data corresponds to $1 - \exp(-\kappa\,\Delta t) \simeq \kappa$, with $\Delta t = 1$ day.

[7]Five primary dealers have created a market in stripped bonds based on OLO09, but this occurred only after the first (351-day) sample period. Thus, the stripping of OLO09 cannot affect the sample results.

bias the trading results in favor of the economic models by eliminating two bonds that are consistently mispriced, we preferred to keep OLO03/09 in the sample.

Like the average cross-sectional , the low MAEs for most bonds (with the exception for OLO03 and 09) seem to suggest that the MAEs may merely reflect purely random bid-ask bounce (which would generate a MAE of, at most, $(|12.5| + |-12.5|)/2 = 12.5$ basis points). However, such a conclusion would be unwarranted. First, there is a substantial MAE for many deposits, too; and as market values for interbank deposits are based on the mean interest rate, bid-ask noise is absent from these data. Second, the last columns of each panel of Table 4 reveal that, for all assets, the first-order autocorrelations in the model residuals are significantly positive. Purely random bid-ask bounce cannot be a source of autocorrelation in pricing errors (as opposed to returns, or residual returns). It follows that the major sources of apparent mispricing must be either highly autocorrelated errors in the specification or estimation of the model, or highly autocorrelated true mispricing, or both, rather than purely random bid-ask bounce. In part II we will have a closer look at the model residuals for the OLOs, and verify whether they allow any profitable trading strategies or successful forecasts about holding period returns.

II. The Information Content in the Model Residuals

One conceptual weakness of models that, like the Vasicek or CIR model, postulate an interest rate or another non-price process as the driving state variable, is that such a model does not take the current term structure as given and is, therefore, likely to deem all outstanding bonds to be mispriced. Clearly, some of this apparent mispricing must be due to model misspecification. On the other hand, in the presence of noise trading by uninformed or time-pressed investors it is quite likely that bonds are, to some extent, effectively mispriced relative to the (unidentified) 'true' model. In this section, we verify whether the apparent mispricing in the Vasicek and CIR models is entirely due to model misspecification and mis-estimation or whether such a model is also able to detect some genuine mispricing due to noise trades. If there is genuine mispricing, trading on the basis of model residuals should be profitable. In short, in this part of the paper we view the CIR and Vasicek estimated term structure models as (somewhat complicated) curve-fitting techniques, and we do not worry about non-constancy of those parameter estimates that, in the logic of the model, should be constant. The focus is on how useful the model residuals are to a bond trader, and whether the economic models outperform the simple spline model for the purpose of identifying mispriced bonds.

This part of the paper is structured as follows. Section II.1 defines the holding period returns and the equilibrium expected holding period returns that serve as benchmarks in our subsequent regression and trading rule tests. We use three alternative benchmark returns. One is the duration ratio model—a single index model that, like the market model for stocks, compares the realized return on the trading portfolio to the return on a diversified portfolio with the same risk (duration). The second benchmark is the return on a portfolio that matches the bond in terms of both duration and convexity. Both these benchmark are rather *ad hoc*, but they have the advantage of being independent of the details of the term structure model upon which the trading rule is based. The last benchmark is the conditional expected bond return implied by the change in the fitted model prices. A first test of the potential usefulness of the term structure residuals is conducted in Section II.2, where we regress each of these measures of abnormal bond returns on the previous trading day's percentage mispricing. The second test is a trading rule test, described in Sections II.3 and II.4. We compute CARs in calendar time for three trading strategies: (i) buy underpriced bonds, (ii) shortsell overpriced bonds, and (iii) combine both. In Section II.3 the weights within each portfolio are proportional to the degree of initial mispricing relative to the model that is being used (Vasicek, CIR, or spline), while in Section II.4 the weights are equal but the deemed mispricing has to exceed a give filter size. Section III concludes the paper.

II.1 Bond Holding Period Returns and Expected Returns

From each day's estimated Vasicek term structure, we compute the day's Vasicek residual for each bond, i.e. the actual bond price minus the model price or fitted value. The procedure is repeated for the CIR and spline models. If a given bond pricing model is correct and reliably estimated, then a positive residual implies that the corresponding bond is overvalued, while a negative model residual implies that the bond is undervalued. Subsequent holding period returns can then be analyzed to verify or falsify that model's diagnosis. In this section we first define the holding period returns, and then describe the three benchmarks that are used to eliminate the "normal" component in these holding period returns.

II.1.1. Holding Period Returns

Let P_t be the bond's effective price (quote price plus accrued interests) for trading day t. The one-day holding period return on the day ending at t is defined as

$$HP_t = \frac{P_t - P_{t-1} + \text{coupon payment}}{P_{t-1}} \quad . \tag{27}$$

To calculate the exact holding period return on a deposit with, initially, N days to go, we should take the value at maturity, $1 + \frac{\text{N days}}{365} \times \text{BIBOR(t,t+N days)}$, and discount it at the next day's (N–1)-day rate:

$$HP_t = \frac{1 + \frac{\text{N days}}{365}\,\text{BIBOR}(t-1,\, t + \text{N days})}{1 + \frac{\text{N}-1 \text{ days}}{365}\,\text{BIBOR}(t,\, t + (\text{N}-1) \text{ days})} - 1\,. \tag{28}$$

In practice, the true interest rate for N–1 days is not available because published rates bear on maturities corresponding to multiples of one month. As the rate for, say, six months minus one day must be very close to the rate for six months, we approximated the true holding period as follows:

$$HP_t = \frac{1 + \frac{\text{N days}}{365}\,\text{BIBOR}(t-1,\, t + \text{N days})}{1 + \frac{\text{N}-1 \text{ days}}{365}\,\text{BIBOR}(t,\, t + \text{N days})} - 1\;, \tag{29}$$

where today's N-day BIBOR replaces the correct variable, today's (N–1)-day BIBOR.

Event studies or trading rule tests in the stock market frequently use benchmarks like the market model or the *ex post* CAPM, a procedure which filters out price changes due to general market movements while simultaneously taking into account differences in market sensitivity (β). When holding period returns are corrected for market movements, the standard error of the abnormal return becomes smaller and the tests more powerful. In the next three sections we propose three alternative benchmark returns that intend to filter out general market movement from the raw returns defined in (27) and (29).

II.1.2. The Model's Implied Normal Daily Return

Define Φ_t as the set of model parameter estimates obtained for days t and t–1. From the estimated model for day t–1, we can compute the model's equilibrium price for any bond i, which we denote by $\hat{P}_{i,t-1}$. We can also compute the fitted next-day equilibrium price using the time-t estimated parameters, denoted by $\hat{P}_{i,t}$. These two equilibrium prices imply an equilibrium holding period return $E_t(HP_{it} \mid \Phi_{t-1}, \Phi_t)$ and a corresponding abnormal return (AR), as follows:

$$E_t(HP_{i,t} \mid \Phi_{t-1}, \Phi_t) = \frac{\hat{P}_{i,t} - \hat{P}_{i,t-1} + \text{coupon payment}}{\hat{P}_{i,t-1}}\;, \tag{30}$$

and

$$AR_{i,t} = HP_{i,t} - E_t(HP_{i,t} \mid \Phi_{t-1}, \Phi_t)\,. \tag{31}$$

While this expected return captures movements of the market as a whole between days t and t–1, and implicitly takes into account the sensitivity of the bond to shifts in the term structure, the procedure has the drawback that it assumes the validity of the very model whose forecasting performance is being tested. This may introduce some degree of circularity into the tests. Alternative benchmark expected returns are proposed in the next two sections.

II.1.3. The Return on a Duration-Matched (DM) Portfolio

The stock market model defines the abnormal return as the estimated residual $\varepsilon_{i,t}$ from the regression $HP_{i,t} = \alpha_i + \beta_i HP_{m,t} + \varepsilon_{i,t}$, where $HP_{i,t}$ is the return on a stock between t and t–1 and $HP_{m,t}$ is the contemporaneous realized return on the market portfolio m. For bonds, estimating β from a times series regression does not work well, since the β-coefficient of a bond is changing with its time to maturity. To avoid time series estimation of β we adopt a duration model similar to the one in Reilly and Sidhu (1989) and Elton and Gruber (1991), who suggest to use the ratio of duration of the individual bond over duration of the market as an approximation for β. The one-factor duration model is

$$HP_{i,t} - \alpha_{i,t-1}\,\Delta t \;=\; \beta_{it}\,[HP_{m,t} - \alpha_{m,t-1}\;\Delta t]\;, \tag{32}$$

where

$\alpha_{i,t-1} = \ln(1+R_{i,t-1})$ = the *p.a.* continuously compounded yield on bond i

$\Delta t = 1/365$

$\beta_{it} = \dfrac{D_{i,t}}{D_{m,t}}$, the relative duration beta

$D_{i,t} = -\dfrac{1}{P_{i,t}} \sum_{j=1}^{N_i} \dfrac{T_{ij}\,CF_{ij}}{(1+R_j)^{T_{ij}}}$, the duration of the bond at the end of the holding period, where N_i is the number of cashflows paid out by bond i

$D_{m,t} = \sum_{i=1}^{M_t} \dfrac{D_{i,t}}{M_t}$, the duration of the equally weighted market portfolio at the end of the holding period, where M_t is the number of CD's and bonds outstanding at t

$HP_{m,t} = \sum_{i=1}^{M_t} \dfrac{HP_{i,t}}{M_t}$, the equally-weighted market return

$\alpha_{m,t} = \sum_{i=1}^{M_t} \dfrac{\alpha_{i,t-1}}{M_t}$

In the presence of noise, we can append an error term to (32) which, in an otherwise efficient market has a zero expectation.[8] Then (32) implies a conditionally expected return equal to

$$E_t(HP_{i,t} \mid HP_{m,t}) = \alpha_{i,t-1}\,\Delta t \; + \; \beta_{it}(HP_{m,t} - \alpha_{m,t-1}\;\Delta t)\;. \tag{33}$$

Conversely, given the change in the term structure as summarized by $HP_{m,t}$, we can compute the abnormal return (AR) as follows:

$$\begin{aligned} AR_{i,t} &\equiv HP_{i,t} - E_t(HP_{i,t} \mid HP_{m,t}) \\ &= HP_{i,t} - [\alpha_{i,t-1}\,\Delta t \; + \; \beta_{i,t}(HP_{m,t} - \alpha_{m,t-1}\;\Delta t)]\;. \end{aligned} \tag{34}$$

The duration model (32) has the advantage that it does not assume the validity of the model that is being tested. This advantage comes at a cost: as is well known, the duration model underlying (33) and (34) assumes that the consecutive term structures are parallel to each other. However, when the intervals are very short (one day) and only medium to long-term bonds are considered, this assumption is less likely to cause major problems. In addition, when the results from (34) agree with the results from (31), the conclusions are fairly robust.

II.1.4. The Return on a Duration and Convexity Matched (DCM) Portfolio

The first order approximation underlying the Duration model may be inadequate for finite holding periods. Among professionals, a second-degree approximation has, therefore, gained popularity. Accordingly, we computed as our third benchmark the return on a portfolio that matches the trading portfolio as far as duration ($-\partial P_i/\partial R\ P^{-1}$) and convexity ($\partial^2 P_i/\partial R^2\ P^{-1}$) are concerned. This duration- and convexity-matched (DCM) portfolio uses three equally-weighted portfolios. Our first portfolio contains the one-, two-, and three-month interbank deposits, the second portfolio the six- and twelve-month deposits, and the last portfolio all OLOs except the OLO that is being matched.

II.2. Regression Test

The question to be answered in the remainder of this paper is whether the amount of mispricing, as identified from the cross-sectional term structure estimates, carries any

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[8]If the market portfolio contains a sufficiently large number of assets, such noise will not materially affect the market return HP_{mt}. In our case the market portfolio contains just the eleven to seventeen assets. With such a small bond portfolio, an abnormally high (low) return in one of the OLO's will also affect the market return upwards (downwards), which then implies that the excess return as computed from (29) is biased towards zero. Thus, the benchmark is overly conservative. Since we do find abnormal returns, the existence of a small-sample bias actually reinforces our conclusions.

information for the subsequent holding period. The logic is as follows. The deviation between the observed price and the model price consists potentially of (i) a purely apparent (spurious) mispricing that is due to model misspecification or mis-estimation, and (ii) genuine mispricing relative to the (unidentified) 'true' valuation model. If all of the observed deviations between model prices and actual quotes stem from model mis-specification or -estimation (component (i)), then there is no reason why this deviation should be informative about subsequent returns. If, on the other hand, a non-trivial part of the deviation corresponds to genuine mispricing, then this mispricing should, on average, disappear over time. That is, truly undervalued (overvalued) bonds should provide above-normal (below-normal) holding period returns later on. To sort out this issue, the holding period returns and the benchmark returns defined in Section I are analyzed in two ways. In this section we discuss the results from regression tests where abnormal returns over the next day are related to the initial mispricing. In subsequent sections we test a trading rule.

To test whether there is a genuine mispricing component in the term structure model residuals, we first focus on the very short run: we regress abnormal rates of returns of a bond between t–1 and t on the bond's percentage residual observed at t–1. Thus, the first regression is

$$AR_{it} = a + b\,\frac{RES_{i,t-1}}{P_{i,t-1}} + e_t\ , \qquad (35)$$

where

$AR_{i,t}$, the abnormal return on bond i, defined as the return in excess of either the model implied return, the DM portfolio return, or the DCM portfolio return

$RES_{i,t-1} = P_{i,t-1} - \hat{P}_{i,t-1}$ where $\hat{P}_{i,t-1}$ is either from the Vasicek, CIR, or spline model

$\hat{P}_{i,t-1}$ is the fitted value of the price at t–1 computed from the time t–1 cross-section analysis

$P_{i,t-1}$ is the actual bond price at t–1

H_1: b=0 and a=0: In setting the next day's price, the market ignores the estimated mispricing, either because the so-called mispricing is irrelevant or because the market does not react within one day

H_2: $b = -1$: All of the estimated mispricing is corrected within one day

H_3: $0 > b > -1$: Some of the estimated mispricing is only apparent, and/or the market needs more than one day to fully correct the error.

To verify to what extent the results reflect bid-ask bias rather than genuine mispricing, we also run a similar regression with the regressor taken from the last trading but one:

$$AR_{it} = a + b\,\frac{RES_{i,t-2}}{P_{i,t-2}} + e'_t\ . \qquad (36)$$

The results for (35) ("Lag = 0") and (36) ("Lag = 1") are presented in Table 5; in Panel 5.A, the Vasicek percentage residual is used as the regressor, while in 5.B and 5.C the regressor is the percentage residual from the CIR and spline model, respecively. Each of these Panels has three subparts depending on the benchmark used in computing the abnormal part of the return—the duration-matched (DM) portfolio, the duration-and-convexity-matched (DCM) portfolio, or the own-model implied return.

First consider the results for regression (35) when the regressor is taken from the close of the day preceding the holding period (columns "Lag = 1"). For the Vasicek model with duration as the benchmark (Table 5.A.1), the abnormal returns from OLOs are significantly negatively related to the time t–1 estimated pricing error for all individual bonds but one, and this one outlier is insignificant; however, no single coefficient comes statistically close to the value -1. When also convexity is introduced as a matching criterion, eleven out of twelve coefficients are again negative, although the number of significantly negative estimates drops to nine (seven) at the 10% (5%) level. For abnormal returns measured relative to the Vasicek model's implied one-day return, shown in Table 5.A.3, all of the b-estimates are significantly negative at the 1% level. The conclusions for the residuals from the CIR model (Tables 5.B.1-3) and the spline model (Tables 5.C.1-3) are qualitatively similar. Almost all estimates are negative, and a clear majority are significantly so. The results when the own-model implied return is taken as the benchmark are, again, the clearest,[9] but results from the DM and DCM models now are more similar than was the case for Vasicek residuals. All this clearly rejects H_1: $b = 0$. Also the hypothesis H_2: $b = -1$ is rejected resoundingly (t-statistics not shown). This leaves us with H_3: there is some information content in the estimated pricing errors, but either part of the so-called error is spurious or the market reacts slowly to such errors.

As discussed before, one weakness of the above tests is that the portfolio of 'overpriced' bonds is more likely to contain ask prices than bid prices, and *vice versa*. Thus, we may be bunching, to some extent, data errors caused by the spread, and these errors should, on average, disappear the next day. To obtain results that are free of the effects of bid-ask bounce, we lag the regressor one day (Tables 5.A.1-C.3, Column "Lag = 1"). As could be expected from the high first-order autocorrelation among model residuals—the regressors in regressions (35) and (36)—, the slope coefficients for equation (36) remain predominantly negative, although they become somewhat lower in the absolute and statistical sense than the coefficients

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[9]This can be explained by the fact that, with the own-model benchmark, the regressand is approximately equal to the change in the regressor. That is, the regression is, approximately,

$$[RES_t - RES_{t-1}]/P_{t-1} = a + b\ RES_{t-1}/P_{t-1} + e_t,$$

so that b is, approximately, unity minus the autocorrelation coefficient of the cross-sectional model residual.

reported before. We again conclude that bid-ask bounce is not the main explanation of our results.

II.3. Trading Rule Tests

To obtain an impression of the economic relevance of the predictability of returns on the basis of deviations between observed and model prices, we test a contrarian trading rule. The trading rule is tested in calendar time rather than in event time, to detect possible subperiods where the rule worked better than average and to avoid problems with event-time tests when there are long runs of under- or overpricing. (See Bjerring *et al.* (1983) for calendar time versus event time tests).

II.3.1. Design of the Test

We only consider OLOs. On any day, we form a portfolio of underpriced bonds (subscript p, short for purchase), a portfolio of overpriced bonds (subscript s, short for sale), weighted by the size of the mispricing ($RES_{i,t-1-l}$, where l is the implementation delay). For example, if the number of underpriced bonds on day t is N_{pt}, then the mean abnormal return for day t on the purchase portfolio is

$$\overline{AR}_{p,t} = \sum_{i=1}^{N_{pt}} \frac{RES_{i,t-1-l}}{\sum_{i=1}^{N_{pt}} RES_{i,t-1-l}} AR_{i,t}\,, \tag{37}$$

where

$\overline{AR}_{x,t}$, x= {p, s}, is the abnormal return on the purchase (sale) portfolio

$N_{x,t}$, x= {p, s}, is the number of bonds in the purchase (sale) portfolio on day t

$RES_{i,t-1-l} = P_{i,t-1-l} - \hat{P}_{i,t-1-l}$, the residual for bond i in the day $t-l$ cross-sectional term structure model;

$AR_{i,t}$ = the abnormal return realized between t–1 and t, defined relative to the DM portfolio, the DCM portfolio, or the own-model implied return.

The parameter l is varied from 0 to 5—that is, the delay in trading is varied from zero to five working days. For $l \geq 1$, there is a delay of at least one day between the decision to trade and the actual implementation, which should eliminate the bid-ask bounce bias that arises for l=0. Similarly, the abnormal return from shortselling the portfolio of overpriced bonds is

$$\overline{AR}_{s,t} = -\sum_{i=1}^{N_{st}} \frac{RES_{i,t-1-l}}{\sum\limits_{i=1}^{N_{st}} RES_{i,t-1-l}} AR_{it} . \tag{38}$$

Before implementing the rule, we first verified the validity of the three benchmarks. Each benchmark is designed so as to yield a zero cross-sectional average abnormal return across all assets—OLOs and bank deposits. In this respect, (34) is similar to the (equally weighted) market model, where by construction the cross-sectional sum of all residuals $\varepsilon_{i,t}$ from $HP_{i,t} = \alpha_i + \beta_i HP_{m,t} + \varepsilon_{i,t}$ is zero every period. However, there is no reason why stock market residuals averaged over a non-random subsample of assets—say, low-β stocks—should be zero. In fact, the size effect familiar from CAPM tests suggests that an average return computed over a subset of low-β stocks would systematically deviate from zero. Likewise, the cross-sectional average abnormal return computed over OLOs only—the high-duration assets—may deviate systematically from zero. To check this, we computed abnormal returns averaged over all OLOs for each day *t*, and cumulated then over all days. The results are shown in Table 6, and depicted in Figure 3. For the three own-model implied return benchmarks, the cumulative abnormal return on the buy-and-hold all-OLO portfolio is consistently small, both statistically and algebraically. For the duration benchmark, however, the cumulative abnormal return on a portfolio of all OLOs gradually increases to reach a grand total of 0.46% over 421 days—not enormous in the economic sense, but nevertheless significant from a statistical point of view. For the DCM benchmark, finally, the cumulative abnormal return on the buy-and-hold portfolio of all OLOs after 351 days is significantly negative (at –0.45%), and then sharply changes to an insignificant 0.17% during the last 70 days. To remove possible bias, we recompute the abnormal return for all benchmarks by subtracting the abnormal return from holding an equally weighted portfolio containing all OLOs. This corrected average abnormal return is labeled $\Delta\overline{AR}$:

$$\Delta\overline{AR}_{x,t} = \sum_{i=1}^{N_{xt}} \frac{RES_{i,t-1-l}}{\sum\limits_{i=1}^{N_{xt}} RES_{i,t-1-l}} H_{i,t-1-l} \left(AR_{i,t} - \sum_{k=1}^{O_t} \frac{AR_{k,t}}{O_t} \right) , \ x = p, s . \tag{39}$$

with O_t = the number of outstanding OLOs at time t, and $H_{i,t-1-l}$ = +1 (–1) of bond i is underpriced (overpriced) on day *t*-1-*l*. $\Delta\overline{AR}_t$ is set equal to zero if the day-t trading portfolio contains no assets. Thus, across all OLOs the modified average abnormal returns are now exactly equal to zero on any given day t. Lastly, the average return from the combined trading portfolio (subscript c) is

$$\Delta\overline{AR}_{c,t} = \frac{\Delta\overline{AR}_{p,t} + \Delta\overline{AR}_{s,t}}{2} \quad . \tag{40}$$

If a trading strategy can outperform the naive buy-and-hold portfolio, $\Delta\overline{AR}_t$ should be positive, on average. To test this, we compute the cumulative average abnormal return, starting from day 1 until day τ (≤ 421):

$$CAR_{x,\tau} = \sum_{t=1}^{\tau} \Delta\overline{AR}_{x,t} \quad , \quad x = p, s, c. \tag{41}$$

where τ is the calendar time measured in trading days. The t-test is based on the Newey-West standard deviation of $\Delta\overline{AR}$ corrected for 4-th degree autocorrelation.

II.3.2. Validity Issues

Conrad and Kaul (1993) discuss three potential pitfalls in tests of contrarian trading rules: compounding of upward bias in asset returns over long holding periods, transaction costs, and bias stemming from bid-ask bounce in the data. In this section, we describe how these three issues are dealt with in our tests.

(i) Upward Drift. As we have seen, the returns we use are corrected for the return on a benchmark portfolio—the model's implied normal return, the duration-matched return, or the Duration and Convexity Matched (DCM) return. Each such benchmark controls for market-wide movements while taking into account also the bond's own characteristics. This procedure largely eliminates potential biases stemming from the compounding of upward drift in asset returns over long holding periods: on any given day, the average cross-sectional abnormal return is exactly equal to zero.

(ii) Transaction costs. In this paper we only present gross returns from trading, that is, abnormal returns before transaction costs, for the following reasons. First, although transaction costs are relevant for arbitrage-motivated trades, the level of these costs very much depends on the size of the trade and the capacity of the trader. Accordingly, we follow Fama (1991)'s suggestion and let the arbitrageur decide whether or not the gross arbitrage returns reported here are larger than the transaction costs. Second, transaction costs are irrelevant if the trade is inspired by exogenous in- or outflows of cash; thus, the gross returns will tell us whether it is worthwhile to select bonds on the basis of fitted bond prices (rather than just picking an issue at random) before such a liquidity-inspired trade is made.

(iii) Bid-ask bounce. If a last-trade price is a bid (ask) price, the bond is more likely to be classified as being underpriced (overpriced). But the trader has to buy an "underpriced"

bond at the ask rather than the bid, and the seller likewise trades at the bid rather than the ask. Thus, if it is assumed that the contrarian trader can immediately deal at the last observed price, the computed return will tend to overstate the true return before transaction costs. To deal with this, we introduce lags of one to five days between the decision to trade and the actual implementation of the trade. For example, in the case of a one-day lag, the trader buys at the close of the trading day following the identification of an underpriced bond. The introduction of such a lag will, on average, eliminate the bias stemming from bid-ask bounce under the assumption that the probability that today's last trade is a purchase is independent of whether the previous day's last trade was a purchase or not. There is no *a priori* reason to doubt this assumption; and direct tests in the US stock market have not rejected this hypothesis (Lehman (1990); Ball, Kothari and Wasley (1995)).

The introduction of lags between the decision to trade and the actual implementation of the transaction is conservative for three reasons. First, although bid-ask bounce should no longer bias the estimated mean excess return once a delay is introduced, the bounce still boosts the variance of the returns and, therefore, makes it harder to obtain statistically significant results. Second, the longer the delay, the more likely that the initial mispricing will have partly or wholly disappeared. In reality, the trader is able to buy or sell at the next opening rather than at the close of the n-th next trading day. Thus, our computed results are likely to be inferior to the ones that can be obtained in practice. A last point, related to the second one, is that in our tests the trader acts on the initial under- or overpricing signal without considering the current price of the bond that was mispriced n days ago. Thus, with a lag between decision and implementation, our tests will include some trades that would have been deemed unprofitable by a real-world trader because the mispricing has disappeared or has even been reversed

II.3.3. Results

The results for the Vasicek, CIR, and spline models are reported in Table 7.A, 7.B, and 7.C, respectively, and shown graphically in Figures 4.A-C. The key findings are as follows. First, across all three models (Vasicek, CIR, spline) and benchmarks (DM, DCM, and own-model implied return), the cumulative abnormal returns in excess of buy-and-hold are positive and significant when there is no delay in trading. The abnormal returns that would be obtained if trading were immediate (at the price that provides the signal) range from 3.5% to almost 6% over a period of about 400 trading days for the DM and own-model benchmarks, and (inexplicably) up to 10% if convexity is taken into account in the matching portfolios. Second, about half of this profit disappears if the trade is delayed one working day. It is impossible for us to say to what extent this drop in profits is due to the elimination of the bid-ask bounce bias rather than genuine corrections in the mid-point prices. However, the results for Lag=1 (that is, when trading takes place with a one-day delay) remain significantly positive. As, in practice, a trader can deal within a shorter delay and with more recent information, we conclude that before-cost profits from bond-picking on the basis of term structure residuals was surely profitable. Third, the adjustment in market prices takes time: trading profits remain positive and significant even if the trade is delayed by four or five days after the signal (see lines "Lag 2-5" in Tables 7). Note also that the trading profits become smaller the longer the delay that is, market prices and model prices do converge over time. This suggests that all models are to some extent able to detect genuine mispricing. Fourth, the abnormal returns that use the own-model implied return as a benchmark are not systematically higher than the abnormal returns computed from the two duration-based models. This suggests that the abnormal returns are not likely to be the result of a circular application of the model. Fifth, for any given trading delay and benchmark, the results from trading on the basis of the spline model residuals are inferior to the results based on the economic-oriented models. Combined with our earlier finding of a better fit in the cross-sectional estimation, this suggests that the spline model, with its traditional six free parameters and its flexible form, is actually over-fitting the data. Conversely, the economic-oriented Vasicek and CIR models, with four parameters and a relatively rigid shape, seem to be better able to distinguish between equilibrium values on the one hand, and mispricing or bid-ask noise on the other. Lastly, we note that for all models, benchmarks, and lags the abnormal returns from selling overpriced bonds are higher than the abnormal returns from buying underpriced issues. This suggests that, at least during the test period, short-selling restrictions may have been important in practice. This is not a foregone conclusion: overpricing should quickly disappear if arbitrageurs have sufficient long positions in the bonds that are overpriced, or if there is a sufficiently large flow of liquidity-motivated sales. An alternative explanation of the persistence of overpricing could be taxes on capital gains; but for Belgian corporations such taxes are waived if the transaction is an "arbitrage" transaction, that is, if the realized capital gains are reinvested within a short period.[10]

II.4. Filter Rule Tests

The contrarian weighting scheme assumes that it is optimal to buy (or shortsell) more of a bond the larger the estimated initial mispricing. In this section we verify this assumption empirically, by having the trade decision depend on the size of the initial mispricing. The

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[10]As evidenced in Table 5, non-zero time-series means of residuals and abnormal returns lead to non-zero intercepts in regressions (36). This could bias the trading rule results. We accordingly re-ran all tests taking into account the bias revealed in the regression intercept, but the conclusions are unaffected by this correction.

results will also shed some light on our conjecture that the spline model's better cross-sectional fit is, actually, the result of overfitting.

The test works as follows. We start on day 25.[11] If, on a given day, an OLO is deemed to be sufficiently overvalued in the sense that its time t–1 estimated pricing error is positive and larger than a certain number of basis points (the filter), we short-sell the overvalued bonds. Similarly, if the residual for an OLO is negative and below (minus) the filter size, we say that the bond is sufficiently undervalued, and we buy and add it to the portfolio. For every given filter size, we again report the results for the purchase-rule and shortselling-rule separately as well as pooled. In the pooled results, the filter is symmetric; that is, the percentage overpricing that triggers the sale is the same as the percentage underpricing that triggers a purchase. The amounts invested in each mispriced bond are assumed to be equal, with day-to-day portfolio rebalancing, such that the abnormal return from the portfolio is given by the equally-weighted average abnormal return, $\overline{AR}_t$, over the N_t bonds in the portfolio:

$$\overline{AR}_t = \sum_{i=1}^{N_t} \frac{AR_{i,t}\, H_{i,t-1}}{N_t} \tag{42}$$

where

$\overline{AR}_t$ = the average abnormal return on day t

N_t = $\sum_{i=1}^{N_t} |H_{i,t-1}|$ is the number of bonds in the portfolio on day t

$AR_{i,t}$ = the abnormal return realized between t–1 and t, defined as in either (31) or (34)

$H_{i,t-1}$ = +1 if the bond is underpriced and if the trading rule allows buying

= –1 if the bond is overpriced and if the trading rule allows shortselling

= 0, otherwise.

As before, the abnormal returns for all benchmarks were corrected for the corresponding abnormal return on the buy-and-hold portfolio of all OLOs. Abnormal returns are then cumulated over time, and t-tests are computed as in Bjerring *et al* (1983).[12]

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[11]We lose 24 days at the beginning of the period to compute standard deviations for the average abnormal returns.

[12]If at least one bond is included in the day-t trading portfolio, we trace back the history of the portfolio's average abnormal return (adjusted for bias, as in (38)) over days t-24, t-23, ..., t-5, and calculate the Newey-West 4th-order autocorrelation adjusted standard deviation, σ_t. $\Delta\overline{AR}_t$ is then standardized into a Student's variable $Z_t = \Delta\overline{AR}_t/\sigma_t$ with, under the null hypothesis that the trading rule yields no systematically positive returns, mean zero and standard deviation $\sqrt{20/(20\text{-}2)}$ = 1.0541. Still under the same null, the statistic

$$\zeta_T = \frac{1}{\sqrt{T-26}} \sum_{t=25}^{T} \frac{Z_t}{1.0541} \tag{II.14}$$

The results for the Vasicek, CIR, and spline models are reported in Tables 8 and 9, and can be summarized as follows. First, for a given filter size and benchmark, trading on the basis of spline model residuals tends to be less profitable than trading on the basis of the economic-oriented models. This again suggests that the spline model is too flexible and, therefore, less able to distinguish mispricing or bid-ask noise from true equilibrium values. However, the spline model's track record looks less bleak when one selects the profit-maximizing filter (abnormal returns for which are printed in boldface in tables 8 and 9): then the spline model does better than the CIR model when the duration-matched portfolio return is taken as the benchmark. (For the own-model implied return benchmark, the spline still comes third; and Vasicek's model still comes in as the clear winner for either benchmark.) Second, when increasing the size of the filter, profits tend to go up first, but then tend to go down. Thus, the contrarian weighting scheme—which places greater emphasis on bonds that are deemed to be highly mispriced—is not optimal. The finding that very large residuals lead to lower average profits suggests that, for all models, large residuals are more likely to be the result of model mis-specification or -estimation rather than mispricing. Third, the optimal filters tend to be smaller for the spline model than for the Vasicek and CIR models. Conversely, large residuals from the spline model (which, one may recall, are also relatively rare) are even more suspect, on average, than large residuals from the Vasicek or CIR models.

III. Conclusions

We estimate 351 to 421 daily Vasicek/CIR bond models on BEF government bonds and interbank deposits, 1991/92. The Vasicek model produces slightly larger MSE's than the CIR model, but the results are otherwise very similar. The cubic spline model, on the other hand, easily beats the two economic models in terms of average fit. Regression tests reveal that part of the deviation between observed price and model price are reversed the next day, and also the second day after the observation of the initial mispricing. This means that the estimated residuals do reflect genuine pricing errors, not just model mis-specification or mis-estimation and bid-ask bounce bias. After correction for market-wide changes, a strategy of buying underpriced bonds or (especially) selling overpriced bonds turns out to be profitable, yielding a significant 5 to 9% more than a buy-and-hold bond portfolio. The best results are obtained if trading is based on the Vasicek and CIR models. The spline model, being more flexible, seems

converges to a unit normal if T is sufficiently large. In this test, $T<420$ because in some days the trading portfolio is empty.

to overfit the data and is, therefore, less able to detect mispricing. Lastly, large model residuals are more likely to be the result of model misspecification or -estimation than are small or medium-sized residuals.

References

Ball, R., "The development, Accomplishmants, and Limitations of the Theory of Stock Market Efficiency", *Managerial Finance* 20(2/3) (1994), 3-48.

Ball, R., S.P. Kothari, and C.E. Wasley, "Can We Implement Research on Stock Trading Rules?", Journal of Portfolio Management, 1995(4), 54-63

Bjerring, J.H., Lakonishok J., and Vermaelen T., "Stock Prices and Financial Analysts' Recommendations," *Journal of Finance* (March 1983), 187-204.

Black, F., and Scholes, M., "The Pricing of Options and Corporate Liabilities," *Journal of Political Economy* 81 (May-June 1973), 637-59.

Brennan, M.J., and E.S. Schwartz, "A Continuous Time Approach to the Pricing of Bonds," *Journal of Banking and Finance* 3 (1979), 133-55.

Brennan, M.J., and E.S. Schwartz, "An Equilibrium Model of Bond Pricing and a Test of Market Efficiency," *Journal of Financial and Quantitative Analysis* (September 1982), 301-29.

Brown, R.H. and S.M. Schaefer, "The Term Structure of Real Interest Rates and the Cox, Ingersoll, and Ross Model." *Journal of Financial Economics* 35 (1994), 3-42.

Brown, S., and Dybvig, P. "The Empirical Implications of the Cox, Ingersoll, Ross Theory of the Term Structure of Interest Rates," *Journal of Finance* (July 1986), 617-630.

Conrad, J. and G. Kaul, "Long-Term Market Overreaction or Biases in Computed Returns?" *Journal of Finance*, (March 1993), 39-63.

Copeland, T., and J. F. Weston. *Financial Theory and Corporate Policy*, 4th ed. Addison-Wesley, Reading, Mass., 1990.

Cox, J.C., J. Ingersoll, and S. Ross, "A Theory of the Term Structure of Interest Rates," *Econometrica*, 53 (1985b), 385-407.

Cox, J.C., J. Ingersoll, and S. Ross, "An Intertemporal General Equilibrium Model of Asset Prices," *Econometrica*, 53 (1985a), 363-84.

De Munnik, J., and P. Schotman, "Cross Sectional versus Time Series Estimation of Term Structure Models: Empirical Results for the Dutch Bond Market." *Journal of Banking and Finance* 18 (1994) 997-1025.

Elton, E.J. and M.J. Gruber. *Modern Portfolio Theory and Investment Analysis*, 4th ed. John Wiley & Sons, New York, 1991.

Fama, E.F., *Foundations of Finance*, Basic Books, New York, 1976

Fama, E.F. "Term-structure Forecasts of Interest Rates, Inflation, and Real Returns," *Journal of Monetary Economics* 25 (1990) 59-76.

Fama, E.F., "Efficient Markets: II", *Journal of Finance* (December 1991), 46, 1575-1617.

Fama, E.F., and J.D. MacBeth, " Risk, Return, Equilibrium: Empirical Tests," *Journal of Political Economy*, 71 (May-June 1973), 607-36.

Hull, J, C., Options, *Futures, and Other Derivative Securities*, Prentice Hall, 1993

Jaffe J.F., "Special Information and Insider Trading," *Journal of Business*, 1974, 410-28.

Lehmann, B.N. "Fads, Martingales, and Market Efficiency." *Quarterly Journal of Economics* (February 1990), 1-28.

Leibowitz, W. L. "Horizon Analysis for Managed Bond Portfolios," *Journal of Portfolio Management* 1, no.3 (Spring 1975), 23-34.

Merton, R.C. "Theory of Rational Option Pricing," *Bell Journal of Economics and Management Science* 4 (1973) 141-83.

Pearson, N.D., and T.S. Sun, "Exploiting the Conditional Density in Estimating the Term Structure: An Application to the Cox Ingersoll, Ross Model," *Journal of Finance*, (September 1994), 1279-1304.

Reilly, F.K., and R.S. Sidhu, "The Many Uses of Bond Duration," *Financial Analysts Journal* (July-August 1980), 59-72.

Vasicek, O. "An Equilibrium Characterization of the Term Structure," *Journal of Financial Economics* 5 (1977) 177-88.

Table 1: Belgian Government Linear Bonds (OLOs)

OLOs are the Belgian government non-callable straight bonds. At the beginning, there are only 6 OLOs available and the number increases to 12 near the end.

March 27, 1991 - December 30, 1992.

Code	Linear Bonds	1st Issue Year	Maturity Year	Coupon Rate(%)	Coupon Due Date
239.45	OLO01	1989	1999	8.25	June 1
245.51	OLO02	1990	1996	10.00	April 5
247.53	OLO03	1990	2000	10.00	Aug. 1
248.54	OLO04	1991	1998	9.25	Jan. 1
249.55	OLO05	1991	1994	9.50	Feb. 28
251.57	OLO06	1991	2003	9.00	March 1
252.58	OLO07	1991	2001	9.00	June 27
254.60	OLO08	1991	1997	9.25	Aug. 29
257.63	OLO09	1992	2007	8.50	Oct. 1
259.65	OLO10	1992	2002	8.75	June 25
260.66	OLO11	1992	1998	9.00	July 30
262.68	OLO12	1992	2012	8.00	Dec. 24

Table 2: Brussels Interbank Offer Rates on Belgian Franc (BIBORs)

Interbank Rates(%) (BIBORs)	27/03/1991 - 16/09/1992 (351 days)				27/03/1991 - 30/12/1992 (421 days)			
	High	Low	Mean	St.Dev.	High	Low	Mean	St.Dev.
1-Month	10.250	8.875	9.421	0.299	10.250	8.563	9.349	0.328
2-Month	10.125	9.837	9.474	0.259	10.125	8.530	9.388	0.318
3-Month	10.063	9.000	9.506	0.228	10.063	8.459	9.407	0.320
6-Month	10.030	9.063	9.534	0.189	10.030	8.063	9.365	0.435
12-Month	10.000	9.125	9.527	0.173	10.000	7.500	9.306	0.550

Table 3: Cross-Sectional Estimation of Term Structure Models

The Vasicek model and the CIR model are estimated using the non-linear least square method but the Cubic Spline fitting is implemented using OLS. Bond invoice prices consist of the daily cross-sectional data of OLOs and short-lived discount bonds converted from BIBORs (par 100) for the period: March 27, 1991 - December 30, 1992 and/or subperiods. Simple annualization is used: daily results times 365.

(A) The Vasicek Model

	Estimated Parameters				Derived Parameters				
	ϕ_0	ϕ_1	ϕ_2	κ	$r^{(b)}$ (%)	$R_L{}^{(c)}$ (%)	$\mu^{(d)}$ (%)	$\sigma^{2(e)}$ (%)	SE[f]
The whole period: March 27, 1991 - December 30, 1992 (421 trading days)									
Max.	0.1561	0.1493	0.0159	0.0247	10.23	9.05	0.183	0.838	0.415
Min.	0.0087	0.0091	-0.0580	0.0015	6.29	7.93	-0.024	-0.010	0.027
Mean	0.0398	0.0368	-0.0022	0.0089	8.83	8.47	0.028	0.068	0.140
St.D.	0.0360	0.0309	0.0169	0.0035	0.56	0.28	0.031	0.080	0.053
t >2.5[a]	34.7%	42.8%	51.5%	42.8%					
t >2	46.1	59.6	67.9	59.4					
t >1.5	62.7	77.0	81.5	76.7					
The first period: March 27, 1991 - September 16, 1992 (351 trading days)									
Max.	0.0644	0.0557	0.0159	0.0241	10.23	9.05	0.183	0.498	0.324
Min.	0.0098	0.0101	0.0003	0.0041	6.29	8.10	-0.016	0.001	0.037
Mean	0.0248	0.0240	0.0048	0.0101	8.76	8.54	0.035	0.077	0.135
St.D.	0.0071	0.0056	0.0025	0.0018	0.55	0.26	0.025	0.056	0.047
t >2.5	22.5%	32.2%	42.7%	32.2%					
t >2	36.2	52.1	61.8	51.9					
t >1.5	56.1	72.4	77.8	72.1					
The second period: September 17 - December 30, 1992 (70 trading days)									
Max.	0.1561	0.1493	0.0045	0.0247	9.80	8.41	0.182	0.838	0.415
Min.	0.0087	0.0091	-0.0580	0.0015	7.65	7.93	-0.024	-0.010	0.027
Mean	0.1148	0.1010	-0.0037	0.0030	9.22	8.13	-0.008	0.024	0.166
St.D	0.0276	0.0253	0.0149	0.0041	0.41	0.12	0.036	0.144	0.070
t >2.5	95.7%	95.7%	95.7%	95.7%					
t >2	95.7	97.1	98.6	97.1					
t >1.5	95.7	100.0	100.0	100.0					

Footnotes under Panel B.

Table 3 —— continued

(B) The CIR model

Only the first period: March 27, 1991 - September 16, 1992 (351 trading days)

	Estimated Parameters				Derived Parameters				
	θ_1	θ_2	θ_3	r (%)	R_L (%)	μ (%)	σ (%)	$\sigma^2 r$ (%)	SE
Max.	0.0262	0.0220	5.1803	9.76	9.05	0.090	648.7	0.917	0.299
Min.	0.0015	0.0015	0.0260	7.63	8.07	-0.005	18.7	0.001	0.011
Mean	0.0103	0.0079	0.2061	8.90	8.52	0.019	217.9	0.144	0.124
St.D.	0.0052	0.0040	0.4300	0.41	0.26	0.016	115.6	0.147	0.054
t>2	59.0%	80.6%	3.7%	94.6%					
t>1.5	78.3%	86.3%	12.0%	96.3%					
t>1	89.2%	92.6%	46.2%	97.4%					

Footnotes also for Panel A:

(a) Percentages of parameter estimates (for each parameter) that have t-ratios (in absolute values) greater than, say, 2.5, in the concerning period.

(b) r is the annualized implied short-term interest rate (i.e., daily rates x 365).

(c) R_L is the annualized yield on a very long term ($T \Rightarrow \infty$) zero coupon bond.

(d) μ is the annualized risk adjusted drift rate of the short-term interest rate. It can be negative.

(e) The annualized implied variance of changes in r is σ^2 in the Vasicek model but $\sigma^2 r$ in the CIR model; it turns out to be negative for the Vasicek model on many cross sections since September 17, 1992. Negative implied variance has been also found by other researchers.

(f) SE (or RMSE) stands for standard error (or root mean squared error) of regression. [e.g., 0.10 means 10 basis points (par 100)].

Table 3 —— continued

(C) The Cubic Spline model

	Estimates of Parameters					SE
	a_1 (x10^3)	a_2 (x10^7)	a_3 (x10^{10})	d_1 (x10^{10})	d_2 (x10^{10})	
	The whole period: March 27, 1991 - December 30, 1992 (421 trading days)					
Max.	-0.2211	2.6599	0.1017	11.3378	0.1008	0.331
Min.	-0.2819	0.1430	-3.4037	-0.1907	-11.4404	0.003
Mean	-0.2548	0.6992	-0.2427	0.2613	- 0.0352	0.091
St.D.	0.0126	0.2818	0.2244	0.5790	0.5594	0.040
t >2.5	100.0%	98.8%	82.4%	66.5%	29.2%	
t >2		99.8	86.7	76.3	37.5	
t >1.5		99.8	89.1	82.0	53.4	
	The first period: March 27, 1991 - September 16, 1992 (351 trading days)					
Max.	-0.2372	1.2159	0.1017	0.6072	0.1008	0.172
Min.	-0.2819	0.1430	-0.5338	-0.1907	-0.0865	0.003
Mean	-0.2583	0.6472	-0.1954	0.1794	0.0069	0.080
St.D.	0.0098	0.2596	0.1441	0.1722	0.0370	0.027
t >2.5	100.0%	98.6%	79.2%	61.5%	25.4%	
t >2		99.7	84.3	71.8	31.9	
t >1.5		99.7	86.9	78.6	48.4	
	The second period: September 17 - December 30, 1992 (70 trading days)					
Max.	-0.2211	2.6599	-0.2888	11.3378	- 0.0224	0.331
Min.	-0.2651	0.7239	-3.4037	0.3358	-11.4404	0.016
Mean	-0.2375	0.9613	-0.4794	0.6691	- 0.2437	0.143
St.D.	0.0107	0.2408	0.3616	1.2890	1.3481	0.052
t >2.5	100.0%	100.0%	98.6%	91.6%	49.3%	
t >2			98.6	98.6	66.2	
t >1.5			100.0	98.6	78.9	

Table 4: Cross-Sectional Model Residuals

Cross-sectional model residuals (pricing errors) are defined as actual bond trade prices minus model prices for each individual bonds (par 100). Maximum, minimum, mean, absolute mean and autocorrelation are reported for the first period: march 27, 1991 - September 16, 1992 (Panel A) for all models but the total period: March 27, 1991 - December 30, 1992, and the second period: September 19, 1992 - December 30, 1992 (Panel B) only for the Vasicek and the Cubic Spline Models.

(A) The first period: March 27, 1991 - September 16, 1992 (351 trading days)

	Obs.	Vasicek Model Residuals					CIR Model Residuals					Cubic Spline Residuals				
		Max.	Min.	Mean	MAE	AC	Max.	Min.	Mean	MAE	AC	Max.	Min.	Mean	MAE	AC
1-Month	351	0.088	-0.136	-0.015	0.022	0.48	0.018	-0.078	-0.015	0.017	0.80	0.116	-0.046	0.006	0.011	0.65
2-Month	351	0.170	-0.150	-0.003	0.024	0.12	0.035	-0.086	-0.017	0.019	0.79	0.114	-0.042	0.004	0.017	0.80
3-Month	351	0.245	-0.149	0.013	0.031	0.24	0.060	-0.118	-0.013	0.020	0.73	0.067	-0.059	-0.002	0.023	0.87
6-Month	351	0.281	-0.150	0.034	0.052	0.55	0.220	-0.142	0.000	0.022	0.43	0.086	-0.069	-0.011	0.027	0.84
12-Month	351	0.308	-0.209	0.019	0.074	0.68	0.271	-0.143	0.010	0.054	0.71	0.105	-0.151	0.015	0.033	0.85
OLO01	314	0.253	-0.227	0.011	0.082	0.78	0.253	-0.305	-0.013	0.090	0.81	0.301	-0.157	0.068	0.097	0.78
OLO02	322	0.335	-0.402	0.023	0.119	0.90	0.287	-0.391	0.016	0.105	0.88	0.117	-0.216	-0.016	0.048	0.78
OLO03	324	0.133	-0.496	-0.195	0.198	0.96	0.045	-0.531	-0.216	0.217	0.93	0.066	-0.289	-0.116	0.118	0.64
OLO04	315	0.170	-0.267	-0.000	0.063	0.78	0.185	-0.263	-0.016	0.071	0.75	0.148	-0.149	0.018	0.045	0.70
OLO05	300	0.302	-0.257	-0.013	0.074	0.72	0.275	-0.176	-0.011	0.049	0.55	0.129	-0.155	-0.006	0.026	0.65
OLO06	318	0.392	-0.257	0.055	0.103	0.84	0.314	-0.415	0.004	0.082	0.77	0.279	-0.063	0.024	0.041	0.88
OLO07	282	0.253	-0.332	-0.036	0.136	0.93	0.207	-0.425	-0.082	0.130	0.86	0.217	-0.211	0.031	0.086	0.86
OLO08	219	0.189	-0.231	0.017	0.057	0.70	0.174	-0.264	0.010	0.063	0.69	0.151	-0.124	0.018	0.048	0.72
OLO09	118	0.700	-0.007	0.252	0.253	0.98	0.643	-0.132	0.198	0.202	0.92	0.003	-0.020	-0.007	0.007	0.47
OLO10	51	0.115	-0.293	-0.067	0.093	0.88	0.096	-0.293	-0.070	0.091	0.86	0.128	-0.143	-0.003	0.062	0.72
OLO11	31	0.130	-0.101	-0.031	0.056	0.74	0.130	-0.101	-0.031	0.056	0.74	0.129	-0.083	-0.001	0.044	0.69

Table 4 —— continued

(B) The whole period and the second period

	Obs.	Vasicek Model Residuals					Cubic Spline Model Residuals				
		Max.	Min.	Mean	MAE	AC	Max.	Min.	Mean	MAE	AC
The whole period: March 27, 1991 - December 30, 1992 (421 trading days)											
1-Month	421	0.088	-0.136	-0.010	0.022	0.46	0.116	-0.060	0.001	0.014	0.83
2-Month	421	0.170	-0.150	-0.001	0.024	0.21	0.114	-0.114	-0.006	0.024	0.91
3-Month	421	0.245	-0.149	0.010	0.029	0.27	0.067	-0.154	-0.014	0.032	0.94
6-Month	421	0.281	-0.150	0.032	0.050	0.47	0.086	-0.106	0.012	0.030	0.87
12-Month	421	0.308	-0.209	0.021	0.071	0.67	0.207	-0.151	0.027	0.043	0.88
OLO01	376	0.464	-0.227	0.025	0.092	0.81	0.370	-0.167	0.071	0.101	0.79
OLO02	383	0.335	-0.402	0.009	0.118	0.89	0.117	-0.347	-0.036	0.063	0.85
OLO03	388	0.156	-0.766	-0.201	0.208	0.84	0.166	-0.735	-0.130	0.136	0.83
OLO04	379	0.370	-0.267	0.012	0.068	0.78	0.199	-0.149	0.019	0.046	0.65
OLO05	354	0.302	-0.257	-0.021	0.074	0.73	0.129	-0.155	-0.006	0.029	0.72
OLO06	381	0.392	-0.257	0.039	0.098	0.82	0.395	-0.160	0.035	0.053	0.84
OLO07	346	0.353	-0.561	-0.072	0.153	0.92	0.217	-0.358	-0.003	0.099	0.90
OLO08	283	0.466	-0.231	0.058	0.089	0.82	0.341	-0.124	0.049	0.072	0.82
OLO09	186	0.700	-0.007	0.234	0.234	0.88	0.112	-0.044	-0.006	0.012	0.64
OLO10	119	0.251	-0.344	-0.059	0.098	0.82	0.228	-0.184	0.038	0.082	0.78
OLO11	95	0.254	-0.153	0.047	0.092	0.81	0.159	-0.117	0.034	0.063	0.70
OLO12	6	0.052	-0.170	-0.101	0.116	-0.26	-0.002	-0.024	-0.016	0.016	-0.42
The second period: September 17 - December 30, 1992 (70 trading days)											
1-Month	70	0.046	-0.046	0.014	0.021	0.85	0.018	-0.060	-0.026	0.028	0.82
2-Month	70	0.067	-0.091	0.010	0.024	0.90	0.030	-0.114	-0.052	0.055	0.84
3-Month	70	0.070	-0.114	-0.006	0.024	0.91	0.035	-0.154	-0.075	0.077	0.84
6-Month	70	0.125	-0.087	0.020	0.037	0.90	0.062	-0.106	-0.017	0.046	0.89
12-Month	70	0.193	-0.093	0.030	0.053	0.77	0.207	-0.031	0.089	0.090	0.69
OLO01	62	0.464	-0.183	0.098	0.145	0.84	0.370	-0.167	0.086	0.123	0.79
OLO02	62	0.276	-0.292	-0.062	0.114	0.74	0.058	-0.347	-0.139	0.142	0.68
OLO03	64	0.156	-0.766	-0.232	0.259	0.94	0.166	-0.735	-0.194	0.221	0.92
OLO04	64	0.370	-0.104	0.073	0.094	0.69	0.199	-0.100	0.025	0.051	0.44
OLO05	54	0.088	-0.182	-0.064	0.072	0.85	0.103	-0.154	-0.004	0.048	0.83
OLO06	62	0.191	-0.238	-0.041	0.068	0.79	0.395	-0.160	0.090	0.116	0.72
OLO07	64	0.024	-0.561	-0.228	0.229	0.77	0.081	-0.358	-0.146	0.153	0.75
OLO08	64	0.466	-0.013	0.203	0.203	0.56	0.341	-0.063	0.153	0.156	0.53
OLO09	68	0.627	0.000	0.202	0.202	0.72	0.112	-0.044	-0.004	0.019	0.65
OLO10	68	0.251	-0.344	-0.051	0.102	0.83	0.228	-0.184	0.072	0.097	0.74
OLO11	64	0.254	-0.153	0.086	0.110	0.77	0.159	-0.117	0.052	0.072	0.64
OLO12	6	0.052	-0.170	-0.101	0.116	-0.26	-0.002	-0.024	-0.016	0.016	-0.42

BIBORs are converted into discount bonds (par 100). MAE stands for mean absolute pricing error or model residual. AC stands for autocorrelation in individual model residuals and all results are significant at 1% level except OLO12 which has only 6 observations.

Table 5: Regression Tests

Abnormal returns (AR_t) are regressed on the previous trading day's Vasicek (Panel A), CIR (Panel B) and Cubic Spline (Panel C) percentage residuals ($Res_{t-1-lag}/P_{t-1-lag}$) respectively. Abnormal returns are gauged by two common benchmarks: (I) the duration ratio model (the duration ratio AR) and (II) the duration-and-convexity-matched (DCM) portfolio return (the DCM AR), and three model specific benchmarks: (III) the Vasicek model's expected return (the Vasicek AR), (IV) the CIR model's expected return (the CIR AR) and (V) the Cubic Spline model's expected return (the Cubic Spline AR). Footnotes are under the last panel.

$$AR_t = a + b\,(RES_{t-1-lag}/P_{t-1-lag}) + \varepsilon_t$$

(t-Ratios in Parentheses)

(A) The Vasicek Relative Pricing Errors

(March 27, 1991 - December 30, 1992: 421 trading days)

(A.1) The Duration Ratio AR as the Regressand (I)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	b	R^2	a (10^{-4})	b	R^2
OLO01	376	0.454	-0.175	0.086	0.398	-0.151	0.066
		(1.38)	(-5.24)**		(1.17)	(-4.73)**	
OLO02	383	0.624	-0.074	0.032	0.542	-0.043	0.009
		(2.36)**	(-3.03)**		(1.99)*	(-2.00)*	
OLO03	388	-2.113	-0.120	0.043	-0.829	-0.047	0.004
		(-2.75)**	(-3.11)**		(-1.51)**	(-1.69)*	
OLO04	379	0.520	-0.134	0.032	0.520	-0.102	0.017
		(1.68)	(-3.93)**		(1.71)*	(-2.71)**	
OLO05	354	0.609	-0.088	0.023	0.611	-0.085	0.021
		(2.52)**	(-2.91)**		(2.35)**	(-2.86)**	
OLO06	381	0.120	-0.117	0.028	-0.388	-0.034	0
		(0.26)	(-2.24)*		(-0.77)	(-0.72)	
OLO07	345	-0.593	-0.057	0.014	-0.474	-0.030	0.002
		(-1.47)	(-2.84)**		(-1.21)	(-1.53)	
OLO08	283	1.458	-0.115	0.024	1.182	-0.059	0.003
		(3.45)**	(-3.74)**		(3.29)**	(-1.24)	
OLO09	186	-2.566	0.046	0	-2.495	0.034	0
		(-2.00)*	(1.03)		(-2.05)*	(0.81)	
OLO10	119	-2.259	-0.256	0.070	-2.578	-0.318	0.106
		(1.84)*	(-2.57)**		(-2.11)*	(-3.52)**	
OLO11	95	1.686	-0.170	0.032	1.697	-0.175	0.032
		(1.86)*	(-2.47)**		(1.88)*	(-2.66)**	
OLO12	6	-15.899	-0.998	0.156	3.447	0.823	0
		(-5.43)**	(-2.51)**		(0.50)	(2.03)*	

Table 5 (Panel A) —— continued

(A.2) The DCM AR as the Regressand (II)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	b	R^2	a (10^{-4})	b	R^2
OLO01	376	0.367 (0.91)	-0.189 (-4.98)**	0.069	0.268 (0.65)	-0.157 (-4.04)**	0.048
OLO02	383	1.304 (2.73)**	-0.116 (-3.01)**	0.023	1.217 (2.47)**	-0.055 (-1.38)	0.003
OLO03	388	-3.660 (-3.72)**	-0.182 (-3.78)**	0.060	-2.215 (-3.04)**	-0.099 (-2.73)**	0.015
OLO04	379	0.820 (2.06)*	-0.114 (-2.16)*	0.012	0.804 (1.94)*	-0.086 (-1.59)	0.005
OLO05	354	1.127 (2.85)**	-0.082 (-1.60)	0.007	1.185 (2.88)**	-0.015 (-0.29)	0
OLO06	381	-0.643 (-0.76)	-0.321 (-3.55)**	0.040	-1.878 (-2.02)*	-0.119 (-1.26)	0.003
OLO07	345	-1.764 (-3.35)**	-0.098 (-3.77)**	0.029	-1.596 (-3.03)**	-0.077 (-2.88)**	0.016
OLO08	283	1.698 (2.97)**	-0.140 (-2.51)**	0.019	1.525 (2.64)**	-0.117 (-1.87)*	0.012
OLO09	186	2.759 (0.52)	-0.223 (-1.09)	0.000	-0.222 (-0.04)	-0.102 (-0.49)	0
OLO10	119	-2.170 (-1.80)*	-0.175 (-1.78)*	0.027	-2.072 (-1.69)*	-0.187 (-1.94)*	0.030
OLO11	95	0.210 (0.14)	0.006 (0.05)	0	0.315 (0.19)	-0.031 (-0.26)	0
OLO12	6	72.993 (6.05)**	4.804 (2.50)**	0.160	39.562 (2.34)**	4.080 (2.16)*	0.148

Table 5 (Panel A) —— continued

(A.3) The Vasicek AR as the Regressand (III)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	b	R^2	a (10^{-4})	b	R^2
OLO01	376	0.277	-0.195	0.096	0.169	-0.146	0.054
		(0.79)	(-5.90)**		(0.46)	(-4.49)**	
OLO02	383	0.088	-0.129	0.069	-0.046	-0.059	0.011
		(0.28)	(-5.02)**		(-0.14)	(-2.44)**	
OLO03	388	-2.825	-0.160	0.074	-0.844	-0.050	0.004
		(-3.85)**	(-4.34)**		(-1.45)	(-1.67)*	
OLO04	379	0.268	-0.251	0.102	0.127	-0.131	0.036
		(0.97)	(-5.94)**		(0.43)	(-3.43)**	
OLO05	354	-0.534	-0.247	0.115	-0.235	-0.078	0.009
		(-1.57)	(-5.81)**		(-0.64)	(-1.75)*	
OLO06	381	0.765	-0.191	0.093	0.065	-0.053	0.005
		(1.99)*	(-4.58)**		(0.15)	(-1.29)	
OLO07	345	-0.545	-0.077	0.034	-0.260	-0.031	0.003
		(-1.46)	(-3.87)**		(-0.70)	(-1.51)	
OLO08	283	1.164	-0.178	0.082	0.701	-0.082	0.014
		(2.90)**	(-5.12)**		(1.82)*	(-1.66)*	
OLO09	186	2.676	-0.115	0.052	1.139	-0.051	0.006
		(2.93)**	(-2.96)**		(1.37)	(-1.27)	
OLO10	119	-1.042	-0.176	0.078	-0.639	-0.144	0.047
		(-1.50)	(-3.01)**		(-0.90)	(-2.55)**	
OLO11	95	0.928	-0.174	0.070	1.006	-0.187	0.079
		(1.44)	(-2.91)**		(1.49)	(-3.11)**	
OLO12	6	-15.165	-1.275	0.917	2.078	0.046	0
		(-25.4)**	(-12.9)**		(1.97)*	(0.18)	

Table 5 —— continued

(B) The CIR Relative Pricing Errors

(March 27, 1991 - September 16, 1992 : 351 trading days)

(B.1) The Duration Ratio AR as the Regressand (I)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	*b*	R^2	*a* (10^{-4})	*b*	R^2
OLO01	313	-0.367	-0.153	0.075	-0.148	-0.074	0.015
		(-1.09)	(-5.11)**		(-0.42)	(-2.36)**	
OLO02	321	0.521	-0.070	0.026	0.383	-0.040	0.006
		(1.84)*	(-2.50)**		(1.35)	(-1.84)*	
OLO03	323	-1.432	-0.072	0.015	-0.715	-0.037	0.001
		(-1.50)	(-1.76)*		(-0.75)	(-0.88)	
OLO04	314	0.045	-0.079	0.024	0.000	-0.085	0.029
		(0.20)	(-2.62)**		(0.000)	(-2.85)**	
OLO05	299	0.471	-0.131	0.028	0.465	-0.092	0.011
		(1.91)*	(-2.66)**		(1.60)	(-1.34)	
OLO06	318	-0.164	-0.099	0.019	-0.273	-0.025	0
		(-0.43)	(-1.94)*		(-0.68)	(-0.65)	
OLO07	281	-0.387	-0.050	0.012	-0.169	-0.015	0
		(-1.01)	(-1.98)*		(-0.46)	(-0.61)	
OLO08	218	0.557	-0.139	0.060	0.536	-0.122	0.045
		(2.00)*	(-3.60)**		(1.87)*	(-3.45)**	
OLO09	117	1.751	-0.107	0.030	0.981	-0.078	0.012
		(1.72)*	(-2.25)*		(0.92)	(-1.64)	
OLO10	50	-1.234	-0.164	0.041	-0.694	-0.116	0.001
		(-1.34)	(-1.63)		(-0.62)	(-0.92)	
OLO11	30	-0.435	-0.194	0.026	-1.498	-0.464	0.341
		(-0.39)	(-1.17)		(-1.96)*	(-3.67)**	

Table 5 (Panel B) —— continued

(B.2) The DCM AR as the Regressand (II)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	*b*	R^2	*a* (10^{-4})	*b*	R^2
OLO01	313	-0.377	-0.158	0.054	-0.143	-0.073	0.009
		(-0.92)	(-4.61)**		(-0.33)	(-2.05)*	
OLO02	321	1.269	-0.102	0.016	1.125	-0.056	0.002
		(2.49)**	(-2.49)**		(2.19)*	(-1.37)	
OLO03	323	-2.722	-0.114	0.023	-2.025	-0.078	0.008
		(-2.23)*	(-2.20)*		(-1.64)	(-1.48)	
OLO04	314	0.521	-0.086	0.008	0.485	-0.076	0
		(1.32)	(-1.90)*		(1.19)	(-1.52)	
OLO05	299	1.115	-0.134	0.009	1.066	-0.064	0
		(2.56)**	(-1.67)*		(2.33)**	(-0.81)	
OLO06	318	-2.031	-0.204	0.010	-2.514	-0.008	0.000
		(-2.03)*	(-2.33)**		(-2.40)**	(-0.10)	
OLO07	281	-1.702	-0.089	0.020	-1.548	-0.069	0.011
		(-3.01)**	(-2.62)**		(-2.68)**	(-2.08)*	
OLO08	218	1.259	-0.206	0.039	1.097	-0.177	0.028
		(2.52)**	(-3.32)**		(2.13)*	(-2.81)**	
OLO09	117	8.672	-0.601	0.032	4.903	-0.419	0.011
		(1.75)*	(-2.87)**		(0.86)	(-1.55)	
OLO10	50	-0.970	-0.057	0	0.751	0.113	0
		(-0.65)	(-0.53)		(0.43)	(0.74)	
OLO11	30	-0.735	-0.247	0	-0.159	-0.158	0
		(-0.45)	(-1.09)		(-0.10)	(-0.68)	

Table 5 (Panel B) —— continued

(B.3) The CIR AR as the Regressand (IV)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	*b*	R^2	*a* (10^{-4})	*b*	R^2
OLO01	313	-0.566 (-1.49)	-0.200 (-6.00)**	0.101	-0.288 (-0.69)	-0.075 (-2.20)*	0.011
OLO02	321	0.254 (0.73)	-0.137 (-4.05)**	0.074	-0.020 (-0.06)	-0.050 (-1.57)	0.007
OLO03	323	-6.617 (-6.55)**	-0.343 (-7.02)**	0.177	-0.196 (-0.15)	-0.012 (-0.20)	0
OLO04	314	-0.354 (-1.11)	-0.255 (-5.72)**	0.126	-0.163 (-0.49)	-0.116 (-2.35)**	0.024
OLO05	299	-0.629 (-1.97)*	-0.456 (-5.90)**	0.223	-0.285 (-0.75)	-0.128 (-1.47)	0.014
OLO06	318	0.049 (0.13)	-0.234 (-4.93)**	0.114	-0.121 (-0.30)	-0.091 (-2.33)**	0.014
OLO07	281	-1.449 (-2.89)**	-0.195 (-5.18)**	0.094	-0.512 (-0.89)	-0.069 (-1.93)*	0.008
OLO08	218	0.387 (1.04)	-0.303 (-5.58)**	0.150	0.165 (0.40)	-0.106 (-1.98)*	0.014
OLO09	117	5.331 (2.87)**	-0.274 (-3.11)**	0.116	2.042 (1.30)	-0.106 (-1.34)	0.009
OLO10	50	-1.918 (-2.12)*	-0.248 (-3.05)**	0.128	-0.504 (-0.43)	-0.117 (-1.05)	0.005
OLO11	30	-0.469 (-0.42)	-0.235 (-1.46)	0.050	-1.197 (-1.44)	-0.419 (-2.85)**	0.255

Table 5 —— continued

(C) The Cubic Spline Model Relative Pricing Errors

(March 27, 1991 - December 30, 1992: 421 trading days)

(C.1) The Duration Ratio AR as the Regressand (I)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	*b*	R^2	*a* (10^{-4})	*b*	R^2
OLO01	376	1.588	-0.225	0.107	1.375	-0.198	0.083
		(4.17)**	(-6.21)**		(3.52)**	(-5.40)**	
OLO02	383	0.178	-0.114	0.022	0.265	-0.074	0.007
		(0.65)	(-2.80)**		(0.94)	(-2.08)*	
OLO03	388	-1.096	-0.097	0.017	-0.628	-0.055	0.003
		(-1.79)*	(-2.05)*		(-1.35)	(-1.51)	
OLO04	379	0.820	-0.240	0.040	0.601	-0.102	0.005
		(2.17)*	(-3.57)**		(1.82)*	(-1.87)*	
OLO05	354	0.649	-0.197	0.021	0.630	-0.176	0.015
		(2.48)**	(-2.36)**		(2.31)*	(-2.04)*	
OLO06	381	-0.427	0.034	0	-0.654	0.052	0
		(-0.95)	(0.64)		(-1.46)	(1.00)	
OLO07	345	-0.223	-0.083	0.016	-0.280	-0.037	0.001
		(-0.60)	(-3.13)**		(-0.74)	(-1.32)	
OLO08	283	1.376	-0.121	0.014	1.126	-0.058	0
		(3.00)**	(-2.66)**		(3.22)**	(-0.92)	
OLO09	186	-1.855	-0.531	0.003	-2.300	-0.797	0.004
		(-2.43)**	(-1.51)		(-2.68)**	(-1.32)	
OLO10	119	0.069	-0.230	0.036	0.273	-0.266	0.046
		(0.01)	(-1.73)*		(0.37)	(-1.97)*	
OLO11	95	1.587	-0.205	0.014	1.496	-0.193	0.011
		(1.68)*	(-1.70)*		(1.67)*	(-1.48)	
OLO12	6	-25.344	-14.009	0.451	-7.549	-3.651	0.
		(-5.32)**	(-3.01)**		(-0.82)	(-0.38)	

Table 5 (Panel C) —— continued

(C.2) The DCM AR as the Regressand (II)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	*b*	R^2	*a* (10^{-4})	*b*	R^2
OLO01	376	1.511 (3.14)**	-0.231 (-5.60)**	0.078	1.222 (2.62)**	-0.196 (-4.53)**	0.055
OLO02	383	0.593 (1.20)	-0.184 (-2.59)**	0.017	0.778 (1.50)	-0.121 (-1.77)*	0.005
OLO03	388	-2.343 (-2.87)**	-0.168 (-2.74)**	0.032	-1.510 (-2.48)**	-0.091 (-1.98)*	0.007
OLO04	379	0.900 (2.05)*	-0.109 (-1.38)	0.002	0.751 (1.63)	-0.023 (-0.28)	0
OLO05	354	1.124 (2.87)**	-0.251 (-2.29)*	0.015	1.108 (2.72)**	-0.163 (-1.41)	0.004
OLO06	381	-1.867 (-1.81)*	-0.003 (-0.03)	0	-2.436 (-2.34)**	0.036 (0.40)	0
OLO07	345	-1.129 (-2.47)**	-0.129 (-3.89)**	0.026	-1.110 (-2.35)**	-0.078 (-2.32)*	0.007
OLO08	283	1.207 (1.96)*	-0.058 (-0.80)	0	1.403 (2.47)**	-0.113 (-1.39)	0.004
OLO09	186	-0.971 (-0.31)	2.203 (1.66)*	0.002	-2.443 (-0.74)	-0.175 (-0.07)	0
OLO10	119	-0.348 (-0.47)	-0.219 (-1.88)*	0.030	-0.481 (-0.60)	-0.135 (-1.06)	0.005
OLO11	95	-0.130 (-0.08)	0.115 (0.56)	0	-0.145 (-0.09)	0.099 (0.50)	0
OLO12	6	43.586 (0.58)	12.535 (0.32)	0	41.237 (2.27)*	31.376 (0.88)	0

Table 5 (Panel C) —— continued

C.3) The Cubic Spline AR as the Regressand (V)

	Obs.	Lag = 0			Lag = 1		
		a (10^{-4})	b	R^2	a (10^{-4})	b	R^2
OLO01	376	1.485	-0.218	0.108	0.830	-0.138	0.043
		(3.90)**	(-6.41)**		(2.45)**	(-3.75)**	
OLO02	383	-0.594	-0.163	0.078	-0.170	-0.030	0
		(-2.91)**	(-4.80)**		(-0.82)	(-0.87)	
OLO03	388	-1.900	-0.166	0.076	-0.663	-0.056	0.006
		(-3.99)**	(-4.03)**		(-1.71)*	(-1.54)	
OLO04	379	0.629	-0.338	0.162	0.263	-0.127	0.020
		(2.82)**	(-7.62)**		(1.10)	(-3.05)**	
OLO05	354	-0.185	-0.293	0.148	-0.073	-0.098	0.013
		(-1.29)	(-5.11)**		(-0.46)	(-1.21)	
OLO06	381	0.473	-0.153	0.070	0.239	-0.078	0.016
		(2.10)*	(-4.31)**		(1.18)	(-2.10)*	
OLO07	345	-0.061	-0.098	0.041	-0.091	-0.026	0
		(-0.22)	(-4.06)**		(-0.31)	(-0.94)	
OLO08	283	1.013	-0.179	0.078	0.565	-0.055	0.004
		(3.16)**	(-4.95)**		(2.08)*	(-1.18)	
OLO09	186	0.074	-0.356	0.114	0.330	0.006	0
		(0.38)	(-1.93)*		(1.68)*	(0.04)	
OLO10	119	0.786	-0.227	0.092	0.205	-0.056	0
		(1.26)	(-3.44)**		(0.29)	(-0.74)	
OLO11	95	0.699	-0.242	0.089	0.647	-0.221	0.069
		(1.21)	(-2.82)**		(1.09)	(-2.52)**	
OLO12	6	-3.808	-2.314	0.803	-1.113	-1.079	0.154
		(-5.98)**	(-7.17)**		(-3.83)**	(-1.93)*	

Footnotes also for Panel A and Panel B:
OLO data are from March 27, 1991 (or from the first trade) through December 30, 1992 (or September 16, 1992 for the CIR model residuals). In all regressions, t-statistics use standard errors which adjust for heteroscedasticity [White (1980)]. One asterisk denotes significance at the 0.10 level and two asterisks denote significance at the 0.05 level for a two-tailed test. The adjusted R^2s less than 0.001 are reported as zero.

Table 6: Buy-and-Hold Portfolio

CARs of the buy-and-hold portfolio, which contains all OLOs available, are reported for the first period: March 27, 1991 - September 16, 1992 (351 trading days) and the whole period: March 27, 1991 - December 30, 1992 (421 trading days), respectively. Abnormal returns of individual bonds are measured by two common benchmarks: (I) the duration ratio model and (II) the duration-and-convexity matched (DCM) portfolio return, and three model specific benchmarks: (III) the Vasicek model's expected return, (IV) the CIR model's expected return and (V) the Cubic Spline model's expected return. For the t-ratios, standard errors use the Newey-West correction with 4 lags. One asterisk denotes significance at 0.05 level and two asterisks at 0.01 level for a one-tailed test.

		351 Trading Days		421 Trading Days	
	Benchmarks	CAR(%)	t	CAR(%)	t
(I)	the Duration Ratio Model	0.50	2.76**	0.46	1.97*
(II)	the DCM Portfolio Return	-0.45	-2.27*	0.17	0.26
(III)	the *Vasicek* Model's Expected Return	-0.08	-0.21	-0.16	-0.37
(IV)	the *CIR* Model's Expected Return	-0.14	-0.35		
(V)	the *Cubic Spline* Model's Expected Return	0.07	0.39	0.14	0.71

Table 7: Profits of Contrarian Strategies

Trading strategies exploit mispriced OLOs using the contrarian weighting scheme on the Vasicek, CIR and Cubic Spline pricing errors (observed at t-1-lag) respectively, and all abnormal profits (CAR) are measured by the cumulative daily average abnormal returns (from t-1 to t) on trading strategies in excess of the daily average abnormal returns on the buy-and-hold portfolio of all traded OLOs. Abnormal returns of individual bonds are measured by two common benchmarks: (I) the duration ratio model and (II) the duration-and-convexity-matched portfolio return; and three model specific benchmarks: (III) the Vasicek model's expected return, (IV) the CIR model's expected return, and (V) the Cubic Spline model's expected return, respectively. Figures in parentheses are t-ratios, in which standard errors use the Newey-West correction with 4 lags. One asterisk denotes significance at 0.05 level and two asterisks at 0.01 level for a one-tailed test.

(A) Benchmark Using the Duration Ratio Model (I)

	CAR (%) in Excess of the Buy-and-Hold								
Lag	Buy Strategies			Short Strategies			Combined Strategies		
	Vasicek	CIR	Spline	Vasicek	CIR	Spline	Vasicek	CIR	Spline
	March 27, 1991 - September 16, 1992 (351 trading days)								
0	3.74	3.19	2.91	4.16	4.03	3.37	3.95	3.61	3.14
	(4.52)**	(4.51)**	(5.05)**	(4.15)**	(4.87)**	(5.45)**	(4.70)**	(5.35)**	(5.89)**
1	1.61	1.15	1.29	3.11	3.19	1.82	2.36	2.17	1.55
	(2.80)**	(2.42)**	(2.64)**	(3.70)**	(4.61)**	(3.56)**	(3.92)**	(4.48)**	(3.81)**
2	1.79	1.59	1.46	2.37	2.67	1.53	2.08	2.13	1.50
	(3.00)**	(3.11)**	(2.90)**	(2.65)**	(3.41)**	(2.97)**	(3.23)**	(3.97)**	(3.77)**
3	1.34	0.58	1.14	2.98	2.96	1.47	2.16	1.77	1.30
	(2.26)*	(1.02)	(2.29)*	(3.19)**	(3.35)**	(3.43)**	(3.52)**	(3.04)**	(3.70)**
4	1.17	1.01	1.13	2.26	1.82	1.19	1.72	1.42	1.16
	(2.29)	(2.09)*	(2.23)*	(2.41)**	(2.09)*	(2.65)**	(2.82)**	(2.68)**	(3.45)**
5	1.09	0.56	0.51	1.96	1.96	0.82	1.52	1.26	0.66
	(2.01)*	(1.29)	(1.01)	(2.13)*	(2.33)**	(1.56)	(2.37)**	(2.26)**	(1.72)*
	March 27, 1991 - December 30, 1992 (421 trading days)								
0	4.14		3.57	4.80		4.09	4.47		3.83
	(4.54)**		(5.37)**	(4.69)**		(6.01)**	(5.09)**		(6.55)**
1	1.66		1.37	3.96		2.42	2.81		1.89
	(2.34)**		(2.37)**	(4.57)**		(4.24)**	(4.26)**		(4.06)**
2	1.83		1.48	2.88		1.71	2.35		1.60
	(2.37)**		(2.57)**	(3.07)**		(2.87)**	(3.19)**		(3.37)**
3	1.44		1.46	3.49		1.68	2.46		1.57
	(2.06)*		(2.66)**	(3.53)**		(3.07)**	(3.55)**		(3.60)**
4	1.51		1.16	2.70		1.01	2.11		1.36
	(2.46)**		(2.35)**	(2.76)**		(1.83)*	(3.22)**		(3.51)**
5	1.24		0.65	2.33		0.43	1.79		0.54
	(1.96)**		(1.16)	(2.36)**		(0.69)	(2.51)**		(1.23)

Table 7 —— continued

(B) Benchmark Using the DCM Portfolio Return (II)

	CAR (%) in Excess of the Buy-and-Hold								
Lag	Buy Strategies			Short Strategies			Combined Strategies		
	Vasicek	CIR	Spline	Vasicek	CIR	Spline	Vasicek	CIR	Spline
	March 27, 1991 - September 16, 1992 (351 trading days)								
0	5.29	3.93	3.55	9.63	8.61	3.33	7.46	6.27	3.44
	(4.68)**	(3.98)**	(4.25)**	(5.19)**	(4.76)**	(3.84)**	(5.62)**	(5.17)**	(5.06)**
1	2.33	1.56	1.45	6.42	5.31	2.09	4.37	3.43	1.77
	(2.49)**	(2.20)*	(1.89)*	(3.53)**	(3.18)**	(2.64)**	(3.66)**	(3.44)**	(2.27)**
2	2.74	2.02	1.74	4.71	4.95	1.41	3.72	3.48	1.58
	(2.80)**	(2.52)**	(2.05)*	(2.38)**	(2.57)**	(1.93)*	(2.79)**	(2.90)**	(2.80)**
3	1.95	0.81	1.28	3.78	3.24	1.64	2.87	2.03	1.46
	(2.12)*	(0.89)	(1.31)	(1.75)*	(1.49)	(2.53)**	(2.19)*	(1.57)	(2.80)**
4	1.65	1.24	0.34	5.74	6.78	1.38	3.70	4.01	0.86
	(2.32)*	(1.76)*	(0.45)	(2.60)**	(3.03)**	(2.09)*	(2.99)**	(3.34)**	(1.81)*
5	1.26	0.69	0.38	5.06	4.06	0.64	3.16	2.37	0.38
	(1.57)	(1.05)	(0.72)	(2.53)**	(2.08)*	(0.91)*	(2.53)**	(2.05)*	(0.72)
	March 27, 1991 - December 30, 1992 (421 trading days)								
0	5.63		4.82	9.68		5.50	7.65		5.16
	(4.55)**		(2.69)**	(4.70)**		(3.52)**	(5.18)**		(3.49)**
1	1.72		3.81	7.33		3.85	4.53		3.83
	(1.36)		(1.90)*	(3.61)**		(2.83)**	(3.22)**		(2.65)**
2	2.75		4.42	5.92		2.80	4.34		3.61
	(2.32)*		(2.01)*	(2.67)**		(2.19)*	(2.88)**		(2.41)**
3	1.83		2.76	4.93		3.06	3.38		2.91
	(1.64)		(1.74)*	(2.13)*		(2.47)**	(2.30)*		(2.39)**
4	2.32		2.12	6.59		2.45	4.46		2.28
	(2.24)*		(1.41)	(2.71)**		(2.05)*	(3.08)**		(1.96)*
5	1.49		1.23	4.63		1.51	3.06		1.51
	(1.54)		(0.83)	(1.98)*		(1.20)	(2.09)*		(1.20)

Table 7 —— continued

(C) Benchmark Using the Corresponding Model's Expected Returns

	CAR (%) in Excess of the Buy-and-Hold								
Lag	Buy Strategies			Short Strategies			Combined Strategies		
	Vasicek (III)	CIR (IV)	Spline (V)	Vasicek (III)	CIR (IV)	Spline (V)	Vasicek (III)	CIR (IV)	Spline (V)
	March 27, 1991 - September 16, 1992 (351 trading days)								
0	4.69	3.65	3.40	4.88	5.53	4.73	4.78	4.59	4.37
	(5.67)**	(5.49)**	(6.94)**	(5.71)**	(6.43)**	(7.70)**	(6.10)**	(6.77)**	(7.72)**
1	1.83	1.96	1.27	2.34	2.85	1.41	2.09	2.41	1.34
	(3.54)**	(3.87)**	(3.04)**	(3.94)*	(4.40)**	(2.76)**	(4.42)**	(4.88)**	(3.14)**
2	2.09	1.55	1.10	1.97	1.49	1.74	2.03	1.52	1.42
	(4.08)**	(3.20)**	(2.36)**	(3.33)**	(1.95)*	(3.65)**	(4.21)**	(2.91)**	(3.31)**
3	1.69	0.76	1.15	1.96	1.29	1.30	1.83	1.03	1.06
	(3.10)**	(1.47)	(1.93)*	(2.99)**	(1.86)*	(2.82)**	(3.69)**	(1.98)*	(2.68)**
4	1.03	0.92	0.84	1.35	1.55	0.95	1.19	1.24	0.89
	(2.10)*	(2.07)*	(1.98)*	(2.18)*	(2.57)**	(1.97)*	(2.59)**	(2.97)**	(2.24)**
5	1.35	0.88	0.45	1.79	1.23	0.32	1.57	1.05	0.38
	(2.94)**	(1.85)*	(1.11)	(3.27)**	(1.96)*	(0.68)	(3.54)**	(2.22)*	(0.98)
	March 27, 1991 - December 30, 1992 (421 trading days)								
0	5.35		4.73	5.75		5.87	5.55		5.30
	(6.05)**		(7.26)**	(6.53)**		(8.98)**	(6.75)**		(8.64)**
1	2.02		1.46	3.07		2.02	2.54		1.74
	(3.34)**		(2.84)**	(4.68)**		(3.60)**	(4.65)**		(3.61)**
2	2.11		1.09	2.49		2.06	2.30		1.58
	(3.39)**		(1.91)*	(3.76)**		(3.93)**	(4.01)**		(3.22)**
3	1.81		1.07	2.59		1.92	2.20		1.50
	(2.83)**		(1.99)*	(3.48)**		(3.54)**	(3.70)**		(3.10)**
4	1.48		1.70	1.58		1.22	1.53		1.19
	(2.58)**		(2.80)**	(2.23)*		(2.29)*	(2.89)**		(2.66)**
5	1.40		0.58	2.05		0.23	1.72		0.40
	(2.53)**		(1.15)	(3.23)**		(0.45)	(3.23)**		(0.90)

Table 8: Profits of Filter Rules

Trading strategies exploit mispriced OLOs using different filters (0-30 basis points) on the previous Vasicek (Panel A), CIR (Panel B) and Cubic Spline (Panel C) percentage pricing errors respectively, and all abnormal profits (CAR) are measured by the cumulative daily average abnormal returns (from t-1 to t) on trading strategies in excess of the daily average abnormal returns on the buy-and-hold portfolio of all traded OLOs. Abnormal returns of individual bonds are measured by four benchmarks: (I) the duration ratio model, and respectively, (III) the Vasicek model's expected return, (IV) the CIR model's expected return and (V) the Cubic Spline model's expected return.

(A) Filters on the Vasicek Relative Pricing Errors

March 27, 1991 - December 30, 1992 (421 trading days)

Filters	Buy Strategies			Short Strategies			Combined Strategies		
(%)	Obs.	CAR	t	Obs.	CAR	t	Obs.	CAR	t
				Benchmark using the Duration Ratio Model (I)					
0.00	396	3.23	3.04**	396	3.22	2.89**	396	2.90	3.01**
0.05	396	3.61	3.36**	396	4.64	2.98**	396	3.76	3.19**
0.10	396	4.03	2.89**	396	5.70	3.09**	396	4.91	3.15**
0.15	396	**4.70**	2.47**	393	**5.91**	4.96**	396	**6.02**	3.13**
0.20	379	2.96	2.47**	323	3.88	2.90*	382	4.43	3.58**
0.25	271	2.35	2.28*	205	2.10	1.42	313	3.04	2.70**
0.30	183	1.22	0.55	108	1.38	-0.70	226	1.92	0.23
				Benchmark using Vasicek Model's Expected Return (II)					
0.00	396	4.12	3.86**	396	3.65	3.16**	396	3.54	3.29**
0.05	396	4.63	4.07**	396	4.92	3.05**	396	4.51	4.00**
0.10	396	5.60	4.67**	396	5.73	2.75**	396	5.99	3.30**
0.15	396	**6.26**	3.19**	393	**6.48**	4.97**	396	**7.30**	4.28**
0.20	379	3.96	5.06**	323	4.84	7.70**	382	6.17	6.65**
0.25	271	2.48	2.78**	205	2.38	5.81**	313	3.51	3.26**
0.30	183	1.36	1.07	108	1.60	2.17*	226	2.27	1.32

See footnotes under Panel C.

Table 8 —— continued

(B) Filters on the CIR Relative Pricing Errors

March 27, 1991 - September 16, 1992 (351 trading days)

Filter	Buy Strategies			Short Strategies			Buy & Short Strategies		
(%)	Obs.	CAR	t	Obs.	CAR	t	Obs.	CAR	t
				Benchmark using the Duration Ratio Model (I)					
0.00	326	2.26	3.28**	326	3.30	2.34**	326	2.23	2.84**
0.05	326	1.99	2.91**	326	**3.63**	2.24*	326	2.79	3.12**
0.10	326	1.73	2.12*	326	3.50	3.41**	326	**3.09**	2.76**
0.15	326	2.40	1.93*	239	2.20	0.51	326	2.76	2.17*
0.20	316	**2.47**	4.33**	123	1.53	0.20	321	2.61	4.79**
0.25	276	1.11	1.15	81	1.28	-0.21	283	1.62	0.69
0.30	186	0.88	1.46	42	0.88	0.93	207	1.47	0.48
				Benchmark using CIR Model's Expected Return (IV)					
0.00	326	2.34	2.69**	326	3.74	4.41**	326	2.52	2.51**
0.05	326	3.11	3.47**	326	**5.14**	5.46**	326	4.09	3.20**
0.10	326	3.80	3.40**	326	4.23	2.63**	326	4.96	3.09**
0.15	326	**5.30**	4.70**	238	2.67	0.44	326	5.67	3.94**
0.20	315	5.26	9.81**	123	2.23	2.55**	320	**5.80**	8.93**
0.25	276	3.11	3.36**	81	1.44	2.61**	283	3.81	3.74**
0.30	186	2.27	4.42**	42	0.76	0.66	207	2.72	3.54**

See footnotes under Panel C.

Table 8 —— continued

(C) Filters on the Cubic Spline Relative Pricing Errors

March 27, 1991 - December 30, 1992 (421 trading days)

Filters	Buy Strategies			Short Strategies			Combined Strategies		
(%)	Obs.	CAR	t	Obs.	CAR	t	Obs.	CAR	t
				Benchmark using the Duration Ratio Model (I)					
0.00	396	2.36	2.35**	396	2.50	2.75**	396	2.29	2.73**
0.05	396	**3.38**	2.44**	396	3.34	1.85*	396	3.13	2.82**
0.10	396	3.10	-6.99**	396	**4.98**	2.76**	396	**4.43**	2.33**
0.15	312	1.34	1.97*	334	3.21	3.14**	352	3.16	1.30
0.20	121	1.14	0.50	191	1.58	1.18	221	1.65	-0.37
0.25	42	0.63	2.07*	36	0.91	1.85*	45	0.99	1.35
0.30	26	-0.09	0.22	23	0.45	0.00	26	0.05	0.29
				Benchmark using Cubic Spline Model's Expected Return (V)					
0.00	396	3.34	4.48**	396	3.26	3.45**	396	3.10	3.29**
0.05	396	**4.71**	5.30**	396	4.95	2.66**	396	4.54	3.08**
0.10	396	3.92	4.02**	396	**5.36**	3.06**	396	**5.12**	2.96**
0.15	312	1.80	3.20**	312	3.03	2.39**	352	3.21	1.96*
0.20	121	1.40	1.18	121	1.62	1.43	221	2.12	1.98*
0.25	42	0.88	3.21**	36	0.74	0.87	45	1.15	1.60
0.30	26	0.05	0.21	23	0.28	0.00	26	0.05	0.26

A buy (sell) portfolio contains those OLOs whose percentage pricing errors are more negative (positive) than a filter. Combined portfolio merges buy and sell strategies. The market index in the duration ratio model is an equally weighted portfolio of all available OLOs and short-term discount bonds converted from BIBOR data. "Observations" refer to number of trading days in which the trading portfolio contains assets. Trading starts on day 25, and the first 25 observations are lost for the calculation of the standard deviation of the first risk-and-control-group adjusted returns for standardization. The t-statistic for filter rules measures the significance of the mean of the daily standardized risk-and-control-group adjusted returns according to the portfolio approach of the calendar time event study, where a strange negative t-value for a positive CAR is possible but should not be a rule. One asterisk denotes significance at 0.05 level and two asterisks at 0.01 level for an one-tailed test. The optimum filter with respect to each trading strategy is shown in bold.

Table 9: Comparison of CAR from Filter Rules among Three Models

Trading strategies exploit mispriced OLOs using different filters (0-30 basis points) on the previous Vasicek, CIR and Cubic Spline percentage pricing errors respectively, and all abnormal profits (CAR) are measured by the cumulative daily average abnormal returns (from t-1 to t) on trading strategies in excess of the daily average abnormal returns on the buy-and-hold portfolio of all traded OLOs. Abnormal returns of individual bonds are measured by four benchmarks: (I) the duration ratio model, and respectively, (III) the Vasicek model's expected return, (IV) the CIR model's expected return and (V) the Cubic Spline model's expected return. The period: March 27, 1991 - September 16, 1992 (351 trading days)

	CAR (%) in Excess of the Buy-and-Hold								
	Buy Strategies			Short Strategies			Combined Strategies		
Filters (%)	Vasicek	CIR	Spline	Vasicek	CIR	Spline	Vasicek	CIR	Spline
	Benchmark using the Duration Ratio Model (I)								
0.00	2.84	2.26	1.95	2.84	3.30	2.14	2.52	2.23	1.92
0.05	3.19	1.99	**3.16**	4.04	**3.63**	2.72	3.26	2.79	2.74
0.10	3.78	1.73	2.38	**4.74**	3.50	**4.19**	4.36	**3.09**	**3.69**
0.15	**4.21**	2.40	0.81	4.36	2.20	2.07	**4.81**	2.76	2.08
0.20	2.38	**2.47**	0.37	2.96	1.53	0.87	3.77	2.61	0.85
0.25	1.64	1.11	0.11	1.69	1.28	0.31	2.45	1.62	0.28
0.30	0.82	0.88	0.00	1.17	0.88	0.00	1.48	1.40	0.00
	Benchmarks using corresponding Model's Expected Returns								
	(III)	(IV)	(V)	(III)	(IV)	(V)	(III)	(IV)	(V)
0.00	3.57	2.34	2.66	3.13	3.74	2.65	3.02	2.52	2.49
0.05	4.12	3.11	**4.14**	4.34	**5.14**	**4.12**	3.99	4.09	3.85
0.10	4.96	3.80	3.41	5.21	4.23	3.98	5.46	4.96	**4.26**
0.15	**5.60**	**5.30**	1.45	**5.09**	2.67	1.64	**6.09**	5.67	2.20
0.20	3.28	5.26	0.54	3.22	2.23	0.93	5.11	**5.80**	1.10
0.25	1.78	3.11	0.14	1.61	1.44	0.32	2.66	3.81	0.30
0.30	0.89	2.27	0.00	1.11	0.76	0.00	1.59	2.72	0.00

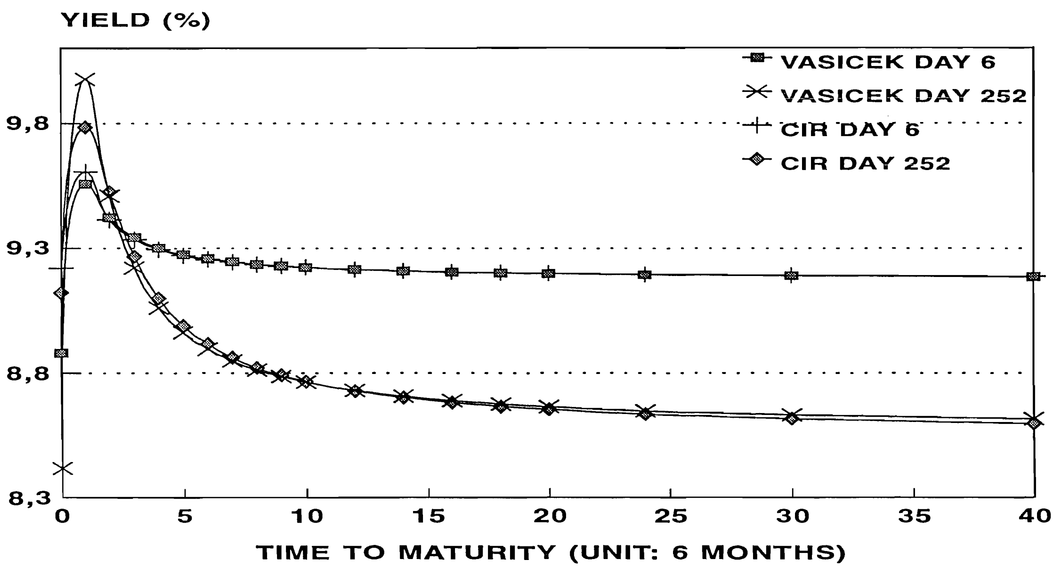
The optimum filter with respect to each trading strategy is shown in bold. CARs are significant at 5% (1% mostly), at least, up to the optimum filters.

Figure 1: Yield Curve Comparison

The Vasicek, the CIR, and the Cubic Spline Yield Curves: Vasicek versus CIR (Panel A) and Vasicek versus Spline (Panel B) are plotted in pair on representative cross sections. The two knots for the Cubic Spline are set at the maturities of 2 and 4 years respectively. Maximum maturity of 20 years shown in the graphics may exceed what can be observed directly from the data. The shortest maturity shown is one day.

(A) Vasicek versus CIR

(A.1) Day 6 (April 5, 1991) and Day 252 (April 14, 1992)



(A.2) Day 120 (September 20, 1991) and Day 351 (September 16, 1992)

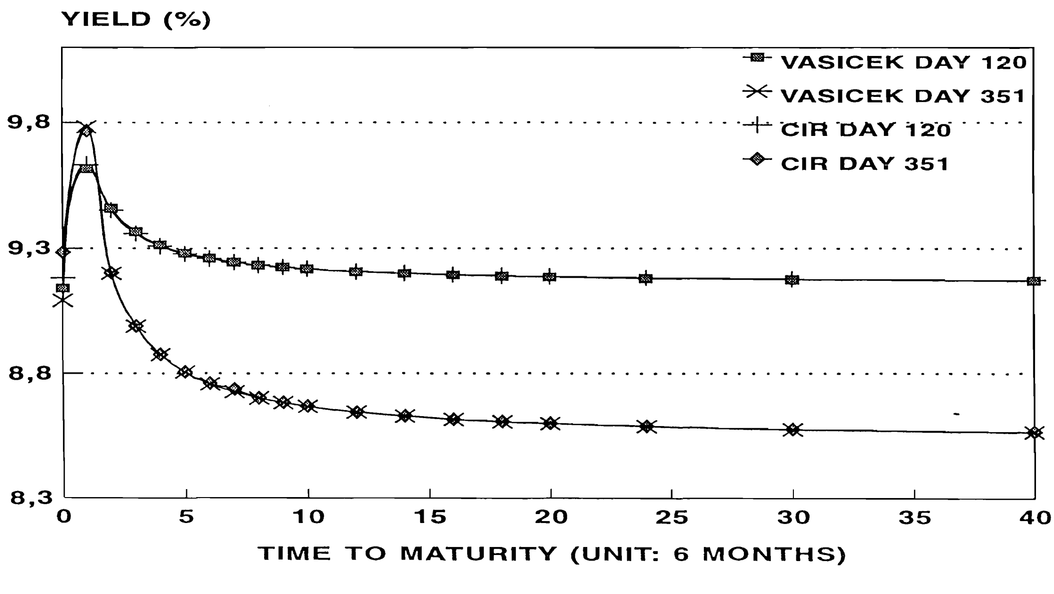
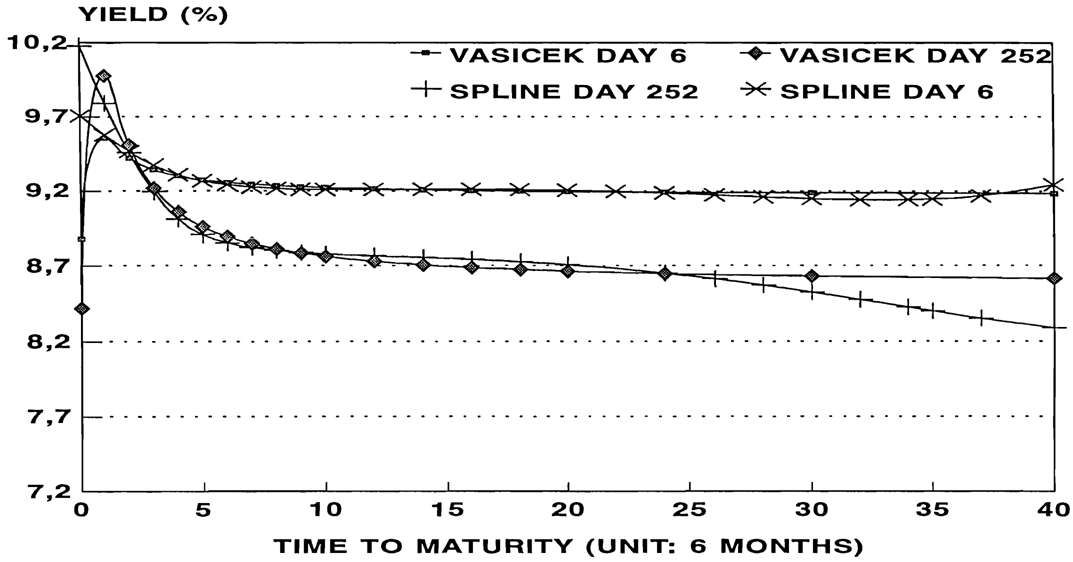


Figure 1 —— continued

(B) Vasicek versus Spline

(B.1) Day 6 (April 5, 1991) and Day 252 (April 14, 1992)



(B.2) Day 351 (September 16, 1992) and Day 421 (December 30, 1992)

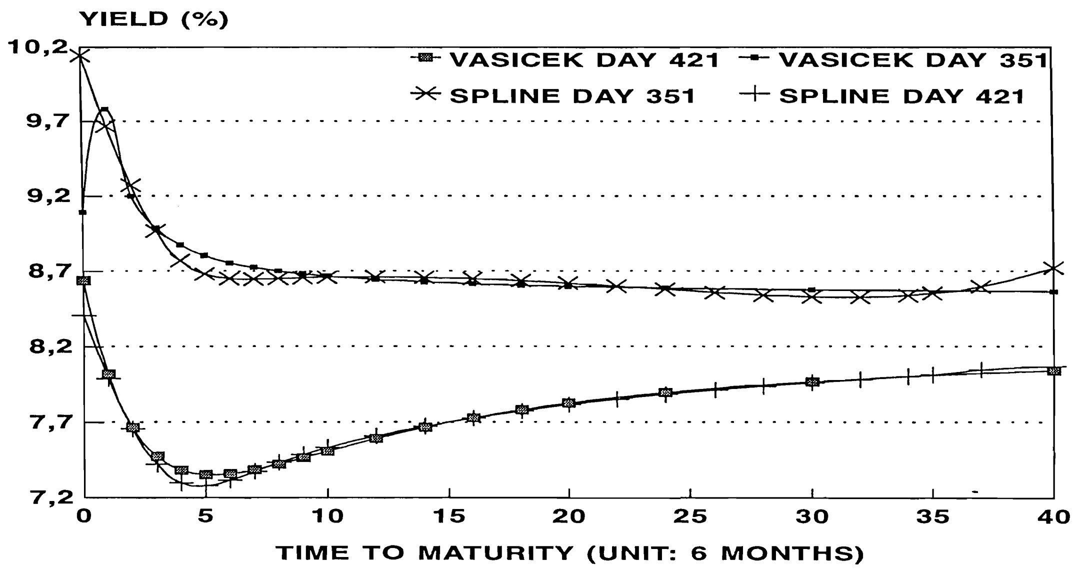
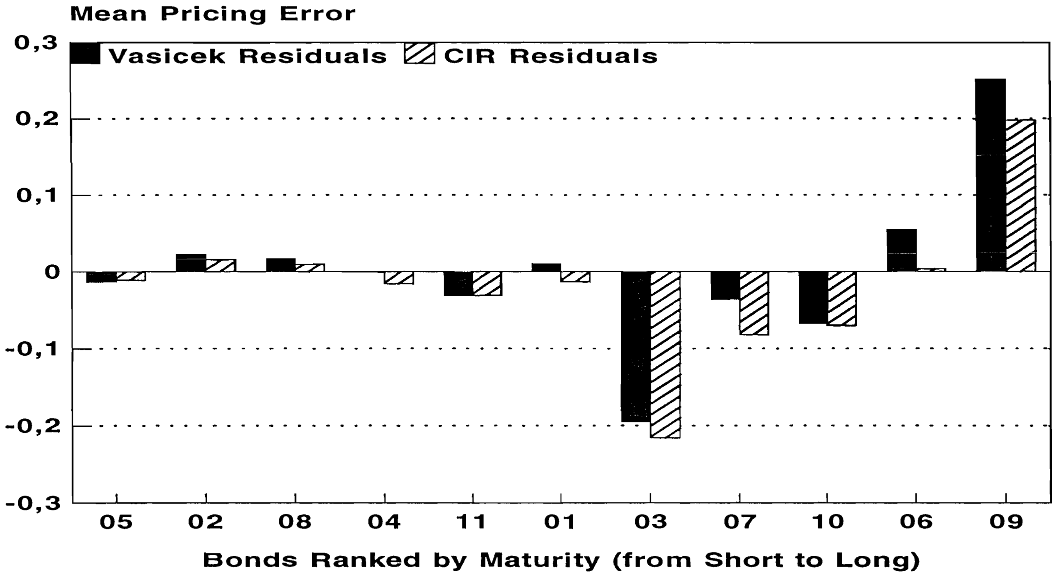


Figure 2: Pricing Error versus Maturity

For the first period: March 27, 1991 - September 16, 1992 (Panel A) and the total period: March 27, 1991 - December 30, 1992 (Panel B), Mean (A.1 and B.1) and absolute mean (A.2 and B.2) pricing errors are used to exhibit the relation of cross-sectional model residuals with maturities. The numbers along the X-axis stand for individual OLOs, which are ranked by maturity from short to long. OLO05 is the bond with the shortest maturity (more than one year) while OLO12 with the longest (less than 20 years).

(A) March 27, 1991 - September 16, 1992 (351 trading days)

(A.1) Mean Pricing Error versus Maturity



(A.2) Mean Absolute Pricing Error versus Maturity

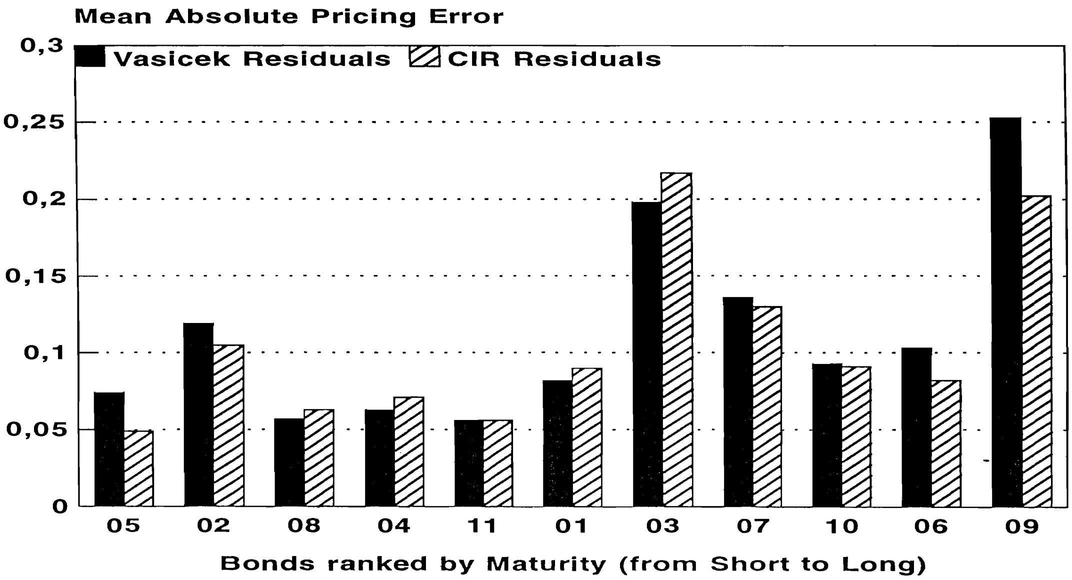
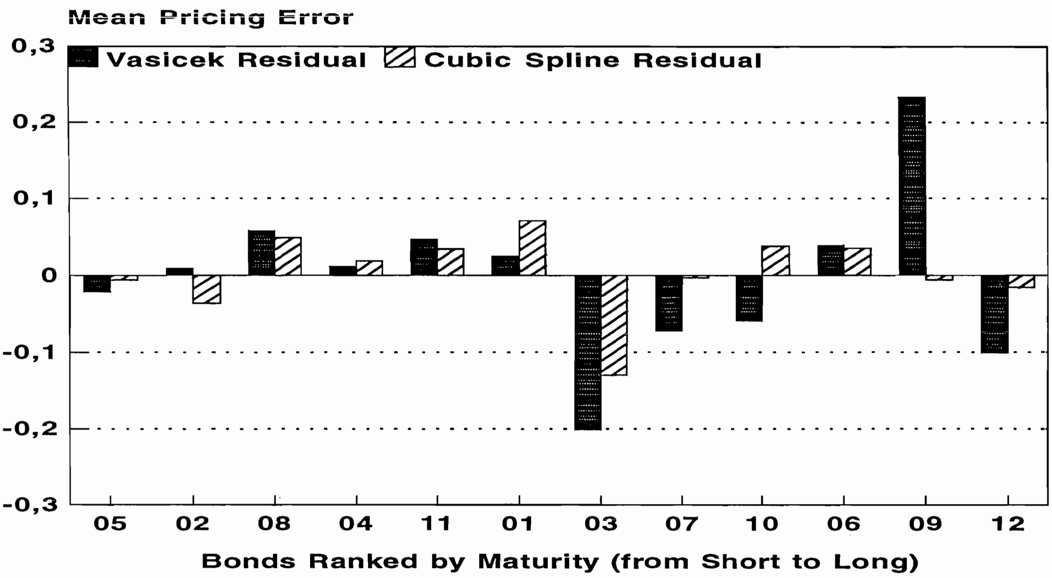


Figure 2 —— continued

(B) March 27, 1991 - December 30, 1992 (421 trading days)

(B.1) Mean Pricing Error versus Maturity



(B.2) Mean Absolute Pricing Error versus Maturity

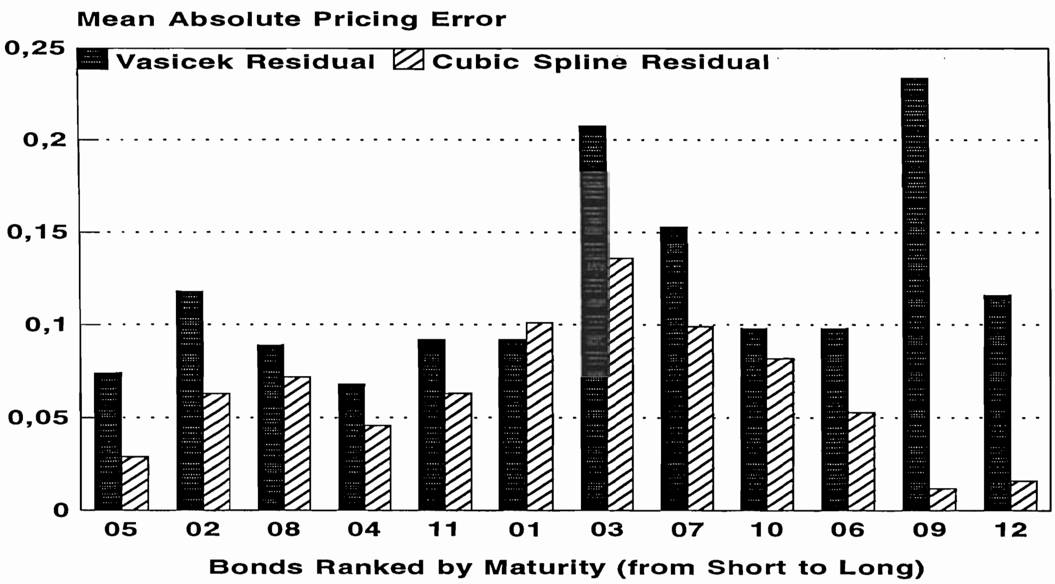
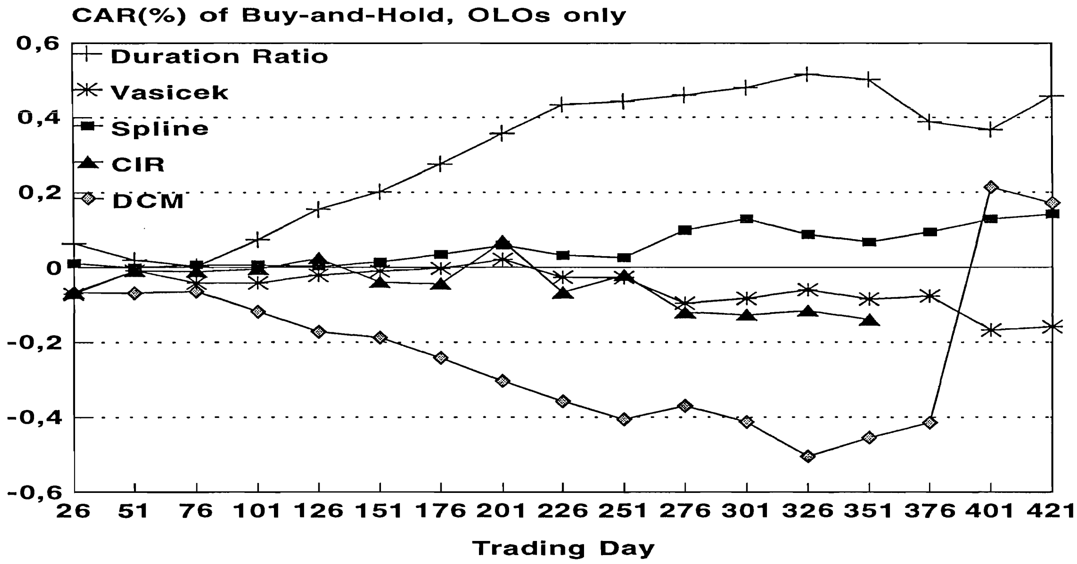


Figure 3: Performance of the Buy-and-hold Portfolio

The buy-and-hold portfolio consists of only traded OLOs. Panel A shows the CARs according to different benchmarks. Abnormal returns of individual bonds are measured by two common benchmarks: the duration ratio model and the duration-and-convexity-matched (DCM) portfolio return, and three model specific benchmarks: Vasicek model's expected return, the CIR model's expected return, and the Cubic Spline model's expected return. The CIR result is only available before September 17, 1992 (or 351 trading days). Panel B shows the total daily cumulative return during the period: March 27, 1991 - December 30, 1992.

(A) CARs by Benchmark



(B) Total Cumulative Return

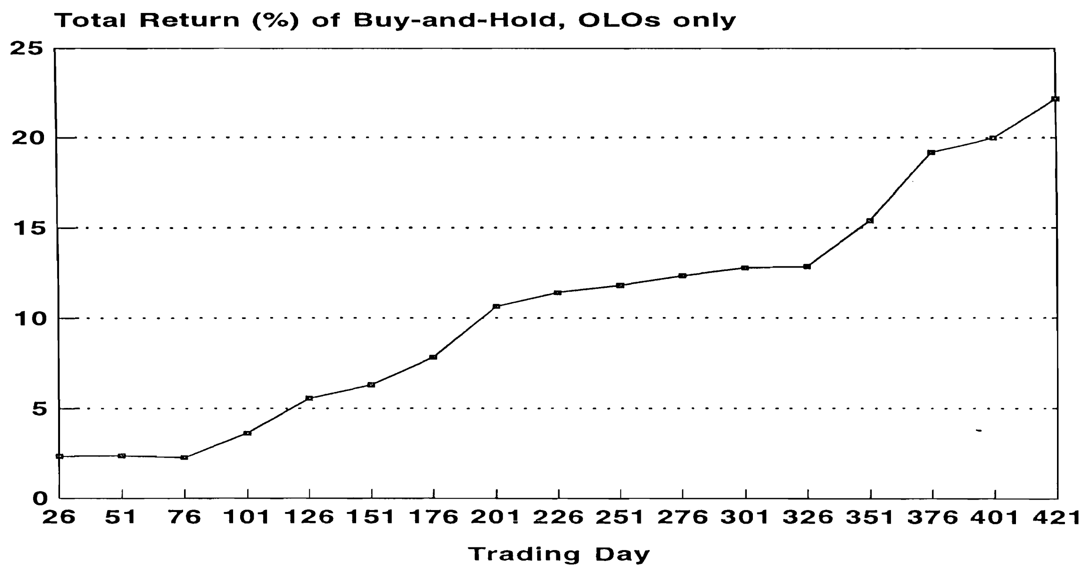
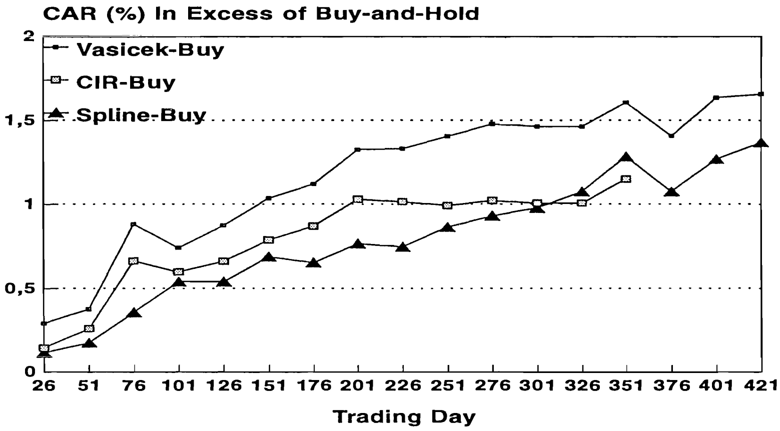


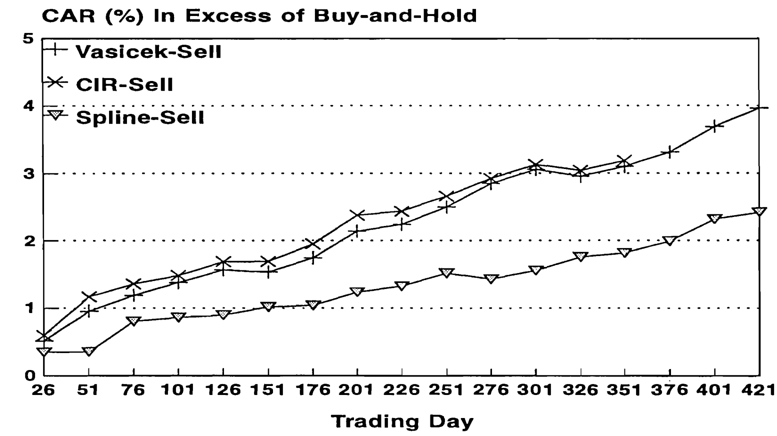
Figure 4: Evolution of CAR from Contrarian Strategies (Skipping One Day)

(A) CAR Using the Benchmark of the Duration Ratio Model

(A.1) Contrarian Buy Strategies Exploiting Underpricing



(A.2) Contrarian Sell Strategies Exploiting Overpricing



(A.3) Contrarian Combined Strategies Exploiting Mispricing

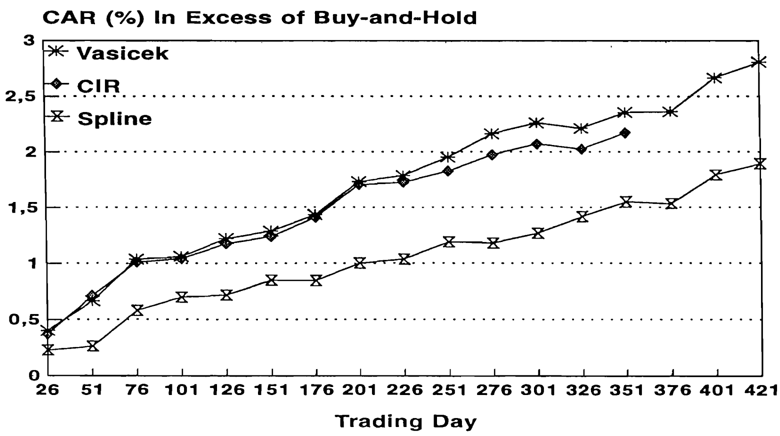
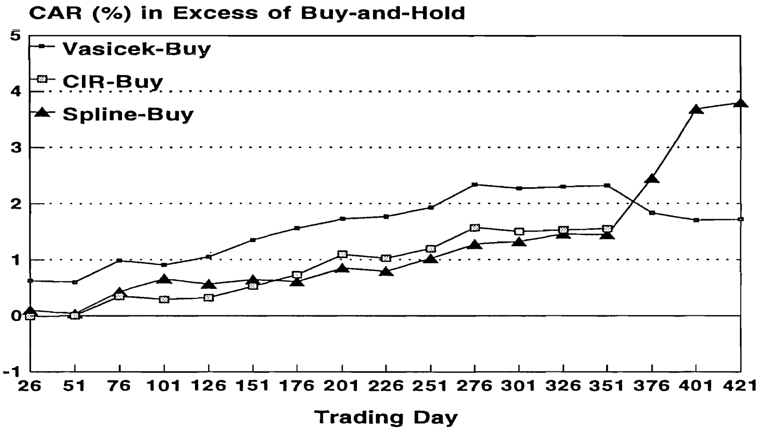


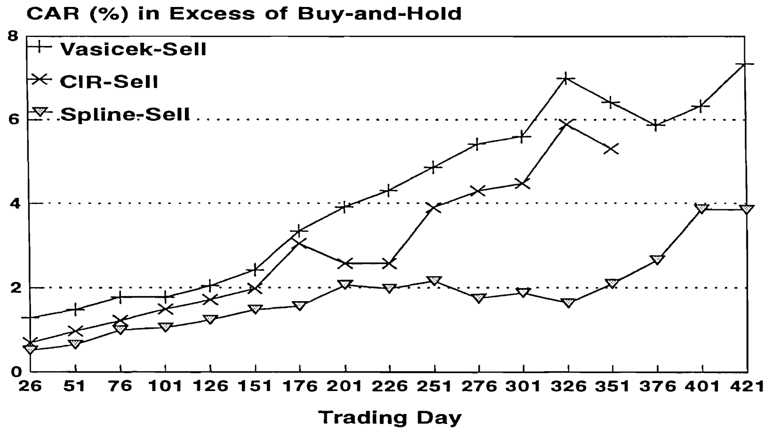
Figure 4 —— continued

(B) CAR Using the Benchmark of the DCM Portfolio Return

(B.1) Contrarian Buy Strategies Exploiting Underpricing



(B.2) Contrarian Sell Strategies Exploiting Overpricing



(B.3) Contrarian Combined Strategies Exploiting Mispricing

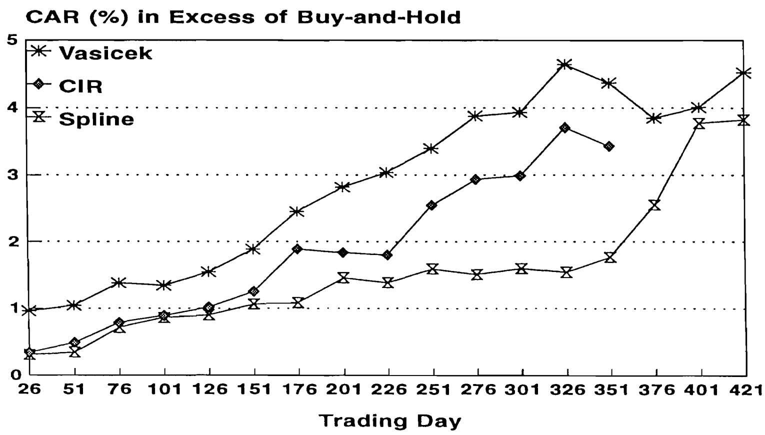
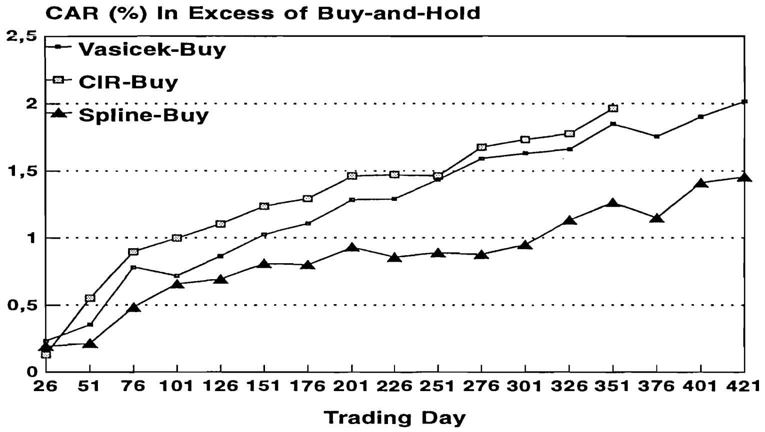


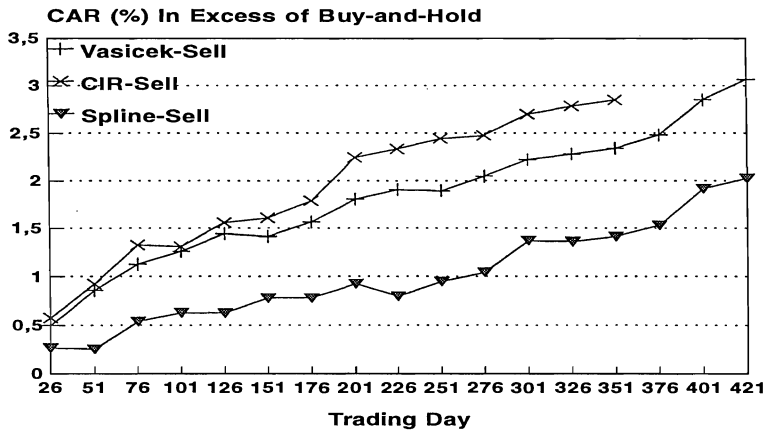
Figure 4 —— continued

(C) CAR Using the Benchmark of Model's Expected Returns

(C.1) Contrarian Buy Strategies Exploiting Underpricing



(C.2) Contrarian Sell Strategies Exploiting Overpricing



(C.3) Contrarian Combined Strategies Exploiting Mispricing