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journal homepage: www.elsevier.com/locate/jfecPricing the term structure with linear regressions[☆]Tobias Adrian^{*}, Richard K. Crump, Emanuel Moench

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ABSTRACT

We show how to price the time series and cross section of the term structure of interest rates using a three-step linear regression approach. Our method allows computationally fast estimation of term structure models with a large number of pricing factors. We present specification tests favoring a model using five principal components of yields as factors. We demonstrate that this model outperforms the [Cochrane and Piazzesi \(2008\)](#) four-factor specification in out-of-sample exercises but generates similar in-sample term premium dynamics. Our regression approach can also incorporate unspanned factors and allows estimation of term structure models without observing a zero-coupon yield curve.

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1. Introduction

Affine models of the term structure of interest rates are a popular tool for the analysis of bond pricing. The models typically start with three assumptions: (1) the pricing kernel is exponentially affine in the shocks that drive the economy, (2) prices of risk are affine in the state variables,

and (3) innovations to state variables and log yield observation errors are conditionally Gaussian (for examples, see [Chen and Scott, 1993](#); [Dai and Singleton, 2000](#); [Collin-Dufresne and Goldstein, 2002](#); [Duffee, 2002](#); [Kim and Wright, 2005](#)). These assumptions give rise to yields that are affine in the state variables and whose coefficients on the state variables are subject to constraints across maturities (for overviews, see [Duffie and Kan, 1996](#); [Piazzesi, 2003](#); [Singleton, 2006](#)). Empirically, the affine term structure literature has primarily used maximum likelihood (ML) methods to estimate coefficients and pricing factors, thus exploiting the distributional assumptions as well as the no-arbitrage constraints.

In this paper, we propose an alternative, regression-based approach to the pricing of interest rates. We start with observable pricing factors and develop a three-step ordinary least squares (OLS) estimator. In the first step, we decompose pricing factors into predictable components and factor innovations by regressing factors on their lagged levels. In the second step, we estimate exposures of Treasury returns with respect to lagged levels of pricing factors and contemporaneous pricing factor innovations.

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In the third step, we obtain the market price of risk parameters from a cross-sectional regression of the exposures of returns to the lagged pricing factors onto exposures to contemporaneous pricing factor innovations. We provide analytical standard errors that adjust for the generated regressor uncertainty. We also discuss the advantages of our method with respect to the recently suggested approaches by [Joslin, Singleton, and Zhu \(2011\)](#) and [Hamilton and Wu \(2012\)](#). In particular, we point out that the assumption of serially uncorrelated yield pricing errors underlying these likelihood-based methods imply excess return predictability not captured by the pricing factors. In contrast, because our approach is based on return regressions, we do not need to make assumptions about serial correlation in yield pricing errors.

We report a specification with five principal components of zero coupon yields as pricing factors. We show that models with fewer factors are rejected in specification tests. The pricing errors in the five-factor specification are remarkably small and return pricing errors do not exhibit autocorrelation. We further find that level risk is priced and that the time variation of level risk is best captured by the second (the slope factor) and fifth principal components. The five-factor specification exhibits substantial variation in risk premiums and at the same time gives reasonable maximal Sharpe ratios.

We next present a four-factor specification following [Cochrane and Piazzesi \(2008, CP\)](#) which includes the first three principal components of Treasury yields and a linear combination of forward rates designed to predict Treasury returns (the CP factor) as pricing factors. Unlike [Cochrane and Piazzesi \(2008\)](#), we allow for unconstrained prices of risk and find that the CP factor significantly prices all factors except slope. The magnitude and time pattern of the price of risk specification of the four-factor CP model is akin to that of the five-factor model, indicating that the two models capture term premium dynamics in a similar way. However, in-sample yield pricing errors are somewhat larger in the four-factor model.

To compare the four- and five-factor models, we perform two out-of-sample exercises. In the first, we use the model-implied term premiums to infer the future path of average short-term interest rates. In the second, we estimate the models using returns on bonds maturing in less than or equal to ten years and then impute the model-implied yields of bonds with longer maturities. In both of these exercises, the five-factor model outperforms the four-factor specification. Hence, we choose the five-factor model to be our preferred specification.

Our procedure can potentially be applied to any set of fixed income securities. In this paper, we use our approach to estimate an affine term structure model from returns on maturity-sorted portfolios of coupon-bearing Treasury securities. The availability of a zero coupon term structure is, therefore, not necessary to estimate the model. Yet, estimation from the returns on maturity sorted bond portfolios with pricing factors extracted from coupon bearing yields generates a zero coupon curve that is very similar to the Fama and Bliss discount bond yields.

We present a number of extensions. First, we show how to estimate the model in the presence of unspanned

factors. Such factors do not improve the cross-sectional fit of yields but do affect the time variation of prices of risk through their predictive power for the yield curve factors. In contrast to the four- and five-factor specifications, incorporating an unspanned real activity factor produces a significant price of slope risk. Second, we show how to impose linear restrictions on risk exposures and market prices of risk in the estimation of the model. Third, we show that the maximal Sharpe ratios implied by the four- and five-factor specifications are very reasonable, with an average level below one and peaks below 2.5. Fourth, we explain how the model can be used to fit the yield curve at the daily frequency. Finally, we show that the implied principal component loadings from the term structure model are statistically indistinguishable from the actual principal component loadings.

Our paper is organized as follows. In Section 2, we present the model and our three-step estimator, and we show how to obtain model-implied yields from the estimated parameters. We further discuss the relation between our approach and other estimation methods in the literature. In Section 3, we present our main empirical findings. Section 4 discusses extensions and robustness checks. Section 5 concludes.

2. The model

In this section, we derive the data generating process for arbitrage-free excess holding period returns from a dynamic asset pricing model with an exponentially affine pricing kernel. We then show how to estimate the model parameters via three-step linear regressions, present their asymptotic distributions, and derive the no-arbitrage cross-equation constraints for bond yields.

2.1. State variables and expected returns

We assume that the dynamics of a $K \times 1$ vector of state variables X_t evolve according to the following vector autoregression (VAR):

$$X_{t+1} = \mu + \Phi X_t + v_{t+1}. \quad (1)$$

This specification of the dynamic evolution of the state variables can be interpreted as a discrete time analog to the intertemporal capital asset pricing model (ICAPM) state variable dynamics of [Merton \(1973\)](#) or the general equilibrium setup of [Cox, Ingersoll, and Ross \(1985\)](#). We assume that the shocks v_{t+1} conditionally follow a Gaussian distribution with variance–covariance matrix Σ :

$$v_{t+1} | \{X_s\}_{s=0}^t \sim N(0, \Sigma), \quad (2)$$

where $\{X_s\}_{s=0}^t$ denotes the history of X_t . We denote $P_t^{(n)}$ the zero coupon Treasury bond price with maturity n at time t . The assumption of no-arbitrage implies (see [Dybvig and Ross, 1987](#)) that there exists a pricing kernel M_t such that

$$P_t^{(n)} = E_t[M_{t+1} P_{t+1}^{(n-1)}]. \quad (3)$$

We assume that the pricing kernel M_{t+1} is exponentially affine:

$$M_{t+1} = \exp(-r_t - \frac{1}{2} \lambda' \lambda_t - \lambda' \Sigma^{-1/2} v_{t+1}), \quad (4)$$

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