Towards a Compact, Empirically Verified Rational Expectations Model for Monetary Policy Analysis

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No. 96-8 November 1996

Working Paper Series

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November 12, 1996

Preliminary. Comments Welcome.

Abstract

This paper extends the sticky-price models of Fuhrer and Moore (1995a,b) to include explicit, optimization-based consumption and investment decisions. The goal is to use the resulting model for monetary policy analysis; consequently, strong emphasis is placed on empirical validation of the model. I use a canonical formulation of the consumer's problem from Campbell and Mankiw (1989), and a time-to-build investment model with costs of adjustment. The restrictions imposed by these models, in conjunction with those imposed on prices and output by the Fuhrer-Moore contracting specification, imply dynamic behavior that is grossly inconsistent with the data. (JEL E52, E43)

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In recent work, George Moore and I developed a small, forward-looking macroeconometric model of the U.S. economy. The primary components of the model were

- A contracting-based price specification that captures the dynamics of prices and inflation, as well as the dynamic interactions among inflation, short-term interest rates, and measures of the output gap (Fuhrer and Moore, 1995a);
- An explicit description of the monetary authority, which controls the short-term nominal interest rate, setting it in response to deviations of inflation from a target value and of output from potential;
- A term structure equation that equates the *ex ante* holding period returns on short-term and long-term bonds; and
- An "I–S" curve that relates the output gap to two of its own lags and one lag of the deviation of the *ex ante* long-term real interest rate from its long-run equilibrium (Fuhrer and Moore, 1995b).

The strength of the model lies in its ability to reproduce the dynamic correlations among inflation, short-term nominal interest rates, and measures of the real output gap. Previous models could not replicate the persistent autocorrelation evident in measures of U.S. inflation or the persistent cross-correlations among inflation, interest rates, and output.

An important shortcoming of the model lies in its incomplete, reduced-form representation of the consumption and investment decisions underlying the I–S curve. In the original model, any links between consumer and firm decisions and their underlying utility and profit functions (and, in turn, the production function and marginal revenue schedules of the firm) are not articulated.

Several recent papers have begun to explore the behavior of an optimizing model with sticky prices. King and Watson (1995) and Kimball (1995) assume imperfect competition as the motivation for sticky prices, while King and Wolman (1995) use a time-dependent price specification based on Calvo (1983). McCallum and Nelson (1996) analyze an "optimizing IS–LM" specification with Fuhrer-Moore (1995a) sticky prices. One of the aims of this research is to determine the extent to which the introduction of sticky prices can fix some of the counterintuitive and data-inconsistent properties of the optimizing models. This paper takes a similar approach, relying on a contract-based price specification to generate price stickiness.

This paper takes several steps in exploring the benefits to extensions of the original models. The motivations for doing so are (1) the construction of a model that combines the desirable price and interest rate components of the earlier models with more fully articulated consumer and firm sectors; and (2) determining the extent to which the previous empirical failings of optimization-based consumption and investment models may be rectified by the explicit inclusion of sticky prices.

I will place significant emphasis on empirical validation in assessing the benefits of these extensions. If the model, incorporating extensions, yields a tolerable deterioration of the likelihood function or, equivalently, continues to mimic the dynamic correlations evident in the data reasonably well, then the extensions and the restrictions that they entail will be judged as improvements. The reason for the focus on empirical success, as opposed to solely theoretical rigor, is that the model is to be used for monetary policy analysis. My bias is that in order to be used for advising monetary policymakers, the model must be shown convincingly to bear some decent resemblance to what goes on in the "real world." The models will all incorporate rational expectations, so that concerns about the simplest form of the Lucas (1976) critique can be addressed.

I will use the closed-form analytical approximation to the canonical consumer's problem from Campbell and Mankiw (1989) for the consumption specification, and a time-to-build investment model with adjustment costs, along the lines of those explored in Taylor (1982), Kydland and Prescott (1982), and Oliner, Rudebusch, and Sichel (1995). I begin with linearized versions of the model for estimation and initial analysis, but I use the full nonlinear versions as well in order to be sure that my conclusions are robust to differences between the linear approximation and the underlying nonlinear model. I will not attempt a full integration of the consumption, investment, and labor decisions, largely because of the difficulties in the labor-leisure trade-off implied by this model, as documented in Mankiw, Rotemberg, and Summers (1985).

To anticipate, I find that, particularly for the investment sector (but also for consumption), combining optimization-based spending behavior with the Fuhrer-Moore (henceforth F-M) sticky price model yields a model whose dynamic implications stand greatly at odds with the dynamics in an unrestricted model. The model implies consumption and investment behaviors that differ significantly from the behavior evident in the data. Indeed, even the behavior of inflation and nominal interest rates deteriorates when combined with the expanded investment and consumption specifications.[1] This behavior differs markedly from the behavior for the F-M model with the simplified I–S curve. I explore in more detail some of the reasons for the failure of this class of models.

In this regard, the results in this paper extend the work of Cogley and Nason (1995), which tests the ability of fairly standard RBC models to repli-

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[1] As shown below, the lack of persistence in output yields a deterioration in the behavior of inflation and interest rates, both of which depend importantly on output dynamics.

cate the autocorrelation properties of output. This paper extends their work by including sticky prices, by estimating the model rather than calibrating it, and by examining the joint dynamic correlation properties of the entire system.

Section 1 briefly reviews the components of the F-M model that I maintain in the current specification. Section 2 describes the consumption specification and preliminary estimation results. Section 3 describes the time-to-build (henceforth TTB) specification for equipment investment and preliminary estimation results. Section 4 examines the system properties of the linear model including both consumption and investment specifications. Section 5 investigates the properties of the linear and nonlinear models with both consumption and investment included. Section 6 concludes.

1 The Fuhrer-Moore model(s)

1.1 Contracting specification

Agents negotiate nominal price contracts that remain in effect for four quarters. The aggregate log price index in quarter t, p_t, is a weighted average of the log contract prices, x_{t-i}, that were negotiated in the current and the previous three quarters and are still in effect. The weights, ω_i, are the proportions of the outstanding contracts that were negotiated in quarters $t-i$,

$$p_t = \sum_{i=0}^{3} \omega_i x_{t-i} \qquad (1)$$

where $\omega_i \geq 0$ and $\sum \omega_i = 1$.[2]

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[2] The distribution of contract prices is a downward-sloping linear function of contract length, $\omega_i = .25 + (1.5 - i)\, s, \quad 0 < s \leq 1/6, \quad i = 0, \ldots, 3$. This distribution depends

The index of real contract prices that were negotiated on the contracts currently in effect is denoted v_t,

$$v_t = \sum_{i=0}^{3} \omega_i (x_{t-i} - p_{t-i}) \tag{2}$$

Agents set nominal contract prices so that the current real contract price equals the average real contract price index expected to prevail over the life of the contract, adjusted for excess demand conditions.

$$x_t - p_t = \sum_{i=0}^{3} \omega_i E_t (v_{t+i} + \gamma \tilde{y}_{t+i}) \tag{3}$$

Substituting equation 2 into equation 3 yields the real version of Taylor's contracting equation,

$$x_t - p_t = \sum_{i=1}^{3} \beta_i (x_{t-i} - p_{t-i}) + \sum_{i=1}^{3} \beta_i E_t (x_{t+i} - p_{t+i}) + \gamma^* \sum_{i=0}^{3} \omega_i E_t (\tilde{y}_{t+i}) \tag{4}$$

In their contract price decisions, agents compare the current real contract price with an average of the real contract prices that were negotiated in the recent past and those that are expected to be negotiated in the near future; the weights in the average measure the extent to which the past and future contracts overlap the current one. When output is expected to be high, the current real contract price is high relative to the real contract prices on overlapping contracts.

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on a single slope parameter, s, and it is invertible. When $s = 0$ it is the rectangular distribution of Taylor (1980), and when $s = 1/6$ it is the triangular distribution.

1.2 The IS curve

In the original F-M model, the simple I–S curve relates the output gap $\tilde{y}_t$ (the deviation of the log of output from the log of potential output) to its own lagged values and one lag of the *ex ante* long-term real interest rate, ρ_t, with the coefficients indicated below

$$\tilde{y}_t = 1.34\tilde{y}_{t-1} - 0.37\tilde{y}_{t-2} - 0.36(\rho_{t-1} - .022) + \epsilon_{yt} \tag{5}$$

where ρ_t is the rational expectation of the discounted weighted average of future short-term real rates, and the parameter estimates are taken from Fuhrer and Moore (1995b).

1.3 The short-term nominal interest rate

For all of the models in this paper, I assume that the monetary authority controls the short-term nominal interest rate f_t (taken to be the federal funds rate). It does so in response to deviations of inflation from its target, and deviations of output from potential, given an interest-smoothing motive. Thus, the behavior of the short rate may be summarized in a simple reaction function

$$f_t = \sum_{i=1}^{l} \alpha_{fi} f_{t-i} + \sum_{j=0}^{m} \alpha_{pj}(\bar{\pi}_{t-j} - \bar{\pi}) + \sum_{k=0}^{n} \alpha_{yk}\tilde{y}_{t-k} + \epsilon_{ft} \tag{6}$$

In section 5 below, I assume $(t-1)$-period expectations, so that the contemporaneous terms in the reaction function represent $(t-1)$-period forecasts of contemporaneous policy goals. This assumption more accurately reflects the information available to the Federal Reserve in setting the federal funds rate than the assumption of contemporaneously available information on prices and output.[3]

2 The consumption sector

In this section, I employ a conventional specification for nondurables and services consumption. The model derives from the standard consumer's problem. The consumer chooses a planned stream of consumption, c_t, to maximize expected utility, subject to the present discounted value of his lifetime assets, given an initial asset stock A_0:

$$\max_{c_t} E_t \sum_{i=0}^{\infty} \delta_i U(c_{t+i}) \; s.t. \; B(A_0, y, c, \rho) \tag{7}$$

where $B(A_0, y, c, \rho)$ is the standard budget constraint, y is real disposable income, and ρ is the real rate of interest. Rather than using the Euler equation for this model, which explicitly determines the change in marginal utility (and under some assumptions, the change in consumption), I prefer a specification that expresses the level of consumption explicitly in terms of current income, lifetime income, and the time-varying real rate of interest.[4]

Arriving at a closed-form expression for consumption is complicated by the nonlinearity of the budget constraint. However, Campbell and Mankiw (1989) derive an approximate linear consumption function for this problem,

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[3] In fact, the most accurate depiction of the information available to the Fed would allow for partial information of the current quarter within the quarter. A modification of this sort lies outside the scope of this paper.

[4] This choice is one of convenience, not substance. An obvious advantage of this form is that we can conveniently answer questions about the effect of expected future income on the current level of consumption. The solution methodology employed throughout allows one to recover the decision rule for the level of consumption from the Euler equation if desired.

which is

$$c_t - y_t = \sum_{i=1}^{\infty} \delta_i(\Delta y_{t+i+1} - \sigma \rho_{t+i+1}) \tag{8}$$

In addition, the consumption function can be augmented to allow for the presence of "rule-of-thumb" consumers who consume only out of current income.[5] If the fraction of such consumers is λ, then Campbell and Mankiw show that the consumption function may be written as

$$c_t - y_t = (1-\lambda)\sum_{i=1}^{\infty} \delta_i(\Delta y_{t+i+1} - \sigma \rho_{t+i+1}) \tag{9}$$

where σ is the intertemporal elasticity of substitution parameter in the utility function. Those consumers who are rule-of-thumbers consume out of current income; those who are permanent income consumers consume out of current and future resources.

2.1 Data and estimation preliminaries

Consumption, c_t, is defined as the log of chain-weighted, per capita, non-durables and services consumption expenditures. Income is the log of chain-weighted, per capita, disposable personal income. The real interest rate is the model-consistent *ex ante* real interest rate, computed as the weighted discounted average of future short-term real interest rates, where the weight in period $t+i$ is $\frac{1}{1+d}\frac{d}{1+d}^{i}$, and the parameter d indexes the duration of the real rate, measured in quarters. I estimate the parameter d jointly with the utility parameters δ and σ and the share of rule-of-thumbers λ. All data are quarterly.

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[5] Campbell and Mankiw provide compelling evidence in their 1989 paper and in companion papers that current consumption responds to predictable changes in current income, consistent with the rule-of-thumb consumer and not with the permanent income consumer.

As indicated, the real rate r will be derived from model-consistent forecasts of short-term real rates. To model the short-term nominal rate and inflation, I use a simple reaction function as described in section 1.3 and the contracting specification of section 1.1. Because the model does not explain all of the components of spending or their relation to income, I require a process for disposable personal income. I assume that disposable income may be well approximated as the sum of a segmented trend Y_t, with breakpoint in 1973, and a deviation from trend, $\tilde{y}_t$, that I model as a reduced-form equation in lags of the income "gap", inflation, and the short rate:

$$\begin{aligned} y_t &= Y_t + \tilde{y}_t \qquad (10) \\ Y_t &= 0.0082 * t - 0.0041 * (t \geq 1973 : IV) + 1.64 \\ \tilde{y}_t &= \sum_{i=1}^{k} (a_i \tilde{y}_{t-i} + b_i \pi_{t-i} + c_i f_{t-i}) \end{aligned}$$

The lag length k is chosen according to conventional criteria to be 3, and the coefficients a_i, b_i, and c_i are estimated via ordinary least squares and held fixed in the estimation below.

2.2 Estimation of the structural parameters

I estimate the intertemporal elasticity of substitution, σ, the time rate of preference δ, the fraction of income accruing to rule-of-thumb consumers, λ, the duration of the real interest rate used in discounting future income, d, and the parameters of the contracting distribution, s and γ, via maximum likelihood, taking the parameters in the backward-looking disposable income process and the funds rate processes as given. The output gap term in the contracting specification is taken to be the disposable income gap described above. The maximum likelihood estimates, asymptotic standard errors and

t-statistics are presented below. The estimation period runs from 1966:I to 1995:IV.[6]

Table 1: Maximum Likelihood Estimates of Consumption Parameters

Parameter	Max. Likelihood Estimate	Std. Error	t-stat.
s	0.0803	0.006	13.0
γ	0.0055	0.003	2.0
σ	0.1780	0.031	5.8
δ	0.5280	0.021	25.6
λ	0.4751	0.131	3.6
d	3.7807	9.253	0.4

The estimated contracting parameters differ insignificantly from the estimates presented in my previous joint work (Fuhrer and Moore 1995a,b). The estimate of the intertemporal substitution parameter lies in the low end of the range presented in Campbell and Mankiw (1989), and is estimated with a good deal of precision. The discount rate, δ, is fairly low, indicating that those consumers who look into the future (permanent income consumers) look only into the very near future. The fraction of income accruing to rule-of-thumb consumers is .48, about the same as the estimates presented in Campbell and Mankiw. The real interest rate, which enters consumption through the intertemporal substitution motive, is estimated to have about a four-quarter duration, although its duration is imprecisely estimated.

To test the robustness of these estimates, I alter the disposable income gap equation to include three lags of the log consumption-income ratio, and re-estimate the parameters. The parameters are similar in some respects, although λ now rises to .94, suggesting essentially no role for future income and real rates in the determination of consumption. σ rises to .46, and the

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[6] As in previous work, I begin the estimation sample in 1966 as it marks the beginning of the use of the federal funds rate as the effective instrument of monetary policy.

real rate duration rises to 10.4. The discount rate δ is now estimated at .998. Overall, these estimates suggest a serious degree of fragility to the specification. The difficulty may be summarized by a positive correlation between λ and δ: if a significant fraction of income accrues to permanent income consumers, then the discount factor must be quite low, effectively discounting away future income and real rate changes. If, however, the fraction of income accruing to permanent income consumers is small, then those consumers are allowed to be forward-looking, because their behavior matters little.[7]

While the residual autocorrelation functions show little evidence of misspecification for the funds rate, inflation, and the disposable income process, the structural residual for the consumption equation (which corresponds to the *level* of consumption) fares less well. The Ljung-Box Q-statistic for the first 12 autocorrelations takes the value 149.4, with p-value essentially zero. By this simple metric, then, the model fails to explain important serial correlation in the nondurables and services consumption data. The likelihood value for the constrained model falls short of that for the unconstrained model by more than 200; the p-value for the likelihood ratio test of the model restrictions essentially takes the value 0.

Figure 1 displays the "fit" of the model, where the fitted values are computed as the difference between the actuals and the structural residuals.[8] The top panel compares the actual and fitted levels, while the bottom panel compares actual and fitted growth rates. As the figure shows, the departures of the model's predictions for the level from the actuals are persistent but not overwhelmingly large. The predictions for the changes in consump-

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[7] Altering starting values for a given disposable income process yields very similar results: if the initial value of λ is set to .9, δ converges to a relatively high number, and vice versa. The global maximum reported in the table above was checked by grid search.

[8] For the consumption specification, this construction is appropriate, because the Jacobian of transformation from the unobserved structural residual to the observed consumption data is one.

tion expenditure, while positively correlated with the actual changes, are far too volatile.[9] What element of the specification leads to this disappointing performance?

Because the specification is simple, it is relatively straightforward to examine its components. Consumption is linked to current income, and to the present discounted value of changes in disposable income and of the expected real interest rate. Although the fraction of income accruing to permanent income consumers is about one-half, the contributions of expected future changes in disposable income and expected real interest rates (scaled by σ) are small because the future is discounted so rapidly. Thus both types of consumers respond largely to current income. The largest errors made by the specification arise in 1973 and 1984, both times during which disposable personal income increased more rapidly than consumption. Thus the excessive dependence of consumption on current income, or equivalently the lack of smoothing, yields the poor performance of the specification.

Overall, I judge the behavior of this consumption specification to be unsatisfactory. The inclusion of current income is likely an improvement over a specification with only forward-looking consumers, but its inclusion causes other problems with the model. In section 5 below, I will use this consumption specification in conjunction with a time-to-build investment specification to determine whether the feedback of consumption and investment back to consumption, through the determination of income, may improve the specification. In that same section, I will use the joint autocorrelation properties implied by this model for consumption, inflation, interest rates, and investment as an important gauge of the overall success of the model.

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[9] The predicted change equals the fitted level described above minus the lagged value of actual log per capita consumption.

3 The time-to-build investment sector

I model investment expenditures on producers' durable equipment in a time-to-build (TTB) framework with costs of adjustment. The specification is essentially as outlined in Oliner, Rudebusch, and Sichel (ORS 1995), which combines the TTB specification of Taylor (1982) with quadratic costs of adjustment.

The model assumes a constant returns to scale Cobb-Douglas production function with elasticities Θ and $1 - \Theta$. Following ORS's notation, let S_t indicate the value of projects started in period t. Denote by ϕ_i the proportion of an investment project's value that is put in place i periods after its start. Investment I_t in period t equals the sum of the value put in place for all projects under way at the time:

$$I_t = \sum_{i=0}^{\tau} \phi_i S_{t-i}$$

where τ is the time to completion for each investment project.

Costs of adjustment are quadratic in the investment-capital ratio, and assume the standard form

$$CA(I_t, K_{t-1}) = (\alpha_0(I_t/K_{t-1}) + (\alpha_1/2)(I_t/K_{t-1})^2)K_{t-1}\,.$$

In the complete, nonlinear model of section 5 below, the discount factor from period $t+s$ back to period t, $\beta^*_{t,s}$ is allowed to vary over time, and is defined as

$$\beta^*_{t,s} = \prod_{j=1}^{s} \beta_{t+j}$$

where β_{t+j} is the time-varying discount rate, and $\beta_{t,s}$ is assumed equal to 1 for $s = 0$.

Defining the firm's discounted profits function in the conventional manner, and using the price of the firm's output as the numeraire, profits P_t are

$$P_t = \sum_{i=0}^{\infty} \beta^*_{t,s}[F(K_{t-1+i}, L_{t+i}) - CA(I_{t+i}, K_{t-1+i}) - p^I_{t+i} I_{t+i} - w_{t+i} L_{t+i}]$$

where p^I is the after-tax price of investment goods, L and w are labor and the nominal wage, respectively. We maximize the expected profit stream, subject to the standard law of motion for capital accumulation (allowing for TTB investment lags),

$$K_t = (1 - \delta_k)K_{t-1} + S_{t-\tau} \tag{11}$$

to arrive at an Euler equation for investment

$$\begin{aligned} &\sum_{i=0}^{\tau} \phi_i[(1-\delta_k)\beta^*_{t,i+1} p^I_{t+i} - \beta^*_{t,i} p_{t+i}] \\ &+\alpha_1 E_t(I_{t+\tau}/K_{t+\tau-1})^2 \beta^*_{t,1+\tau} \\ &+\alpha_1 \sum_{i=0}^{\tau} \phi_i (1-\delta_k)[\beta^*_{t,i+1}(I_{t+i+1}/K_{t+i}) - \beta^*_{t,i}(I_{t+i}/K_{t+i-1})] \\ &+\Theta(Y_{t+\tau}/K_{t+\tau-1})\beta_{t,i+\tau} \\ &= -\alpha_0 \sum_{i=0}^{\tau} \phi_i(1-\delta_k)[\beta_{t,i+1} - \beta_{t,i}] \end{aligned} \tag{12}$$

where Y_t is total output, defined by the Cobb-Douglas production function.

3.1 Data and estimation preliminaries

For the investment series I_t, I use BEA's quarterly chain-weighted series for investment in producers' durable equipment. I assume that $\tau = 3$, so that all projects take four quarters to complete. The capital stock is interpolated from the BEA's annual series. The real after-tax price of investment goods is constructed from the relative price of investment goods, the investment tax credit, the corporate tax rate, and the present value of future depreciation allowances, as in the Federal Reserve Board's quarterly econometric model.[10] The discount rate is defined as one over one plus the model-consistent real rate of interest, with a duration to be estimated.

For the first pass at estimation and analysis of the investment sector of the model, I make a few simplifying assumptions. First, I assume that the discount rate β is a fixed constant (this assumption will be relaxed below). As a result, the discount factors $\beta^*_{t,s}$ reduce to powers of β. Second, I note that with this simplification, the model is linear in the variables p^I, I_t/K_{t-1}, Y_t/K_{t-1}, and $(I_t/K_{t-1})^2$, although it is nonlinear in parameters. Thus I estimate the structural parameters in the model in a linear rational expectations framework with these variables. The drawback, of course, is that the relationships between the ratios and the levels of investment, capital, and output are not enforced; neither is the relationship between the investment-capital ratio and its square. These restrictions will be enforced below.

In order to form expectations of the future variables in equation 13, we must include processes for the capital-output ratio, the square of the investment-capital ratio, and the real after-tax price of investment goods. So as not to impose any more restrictions than necessary on the estimation step, I model these variables as equations in a vector autoregression that includes three lags of each of these variables and three lags of the investment-capital ratio, and three lags of the federal funds rate, inflation, and the GDP gap.[11]

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[10] See Brayton and Mauskopf (1985).

[11] The lag length is chosen according to the Akaike and Schwarz-Bayes information criteria.

I estimate the VAR in a preliminary stage using ordinary least squares; its coefficients are held fixed in the maximum likelihood estimation described below.

3.2 Estimation results

The Euler equation is estimated on the quarterly data via maximum likelihood over the same sample as the consumption equation (1966:I-1995:IV). In initial estimates, the data could not identify the three independent TTB weights, so they are assumed to lie on a straight line, although they must be non-negative and sum to one. The one free parameter that describes the TTB weight distribution is the slope, denoted s_k below.

The uniqueness and stability of the model are surprisingly sensitive to small perturbations in the TTB weights, maintaining the sum constraint. Starting from parameters that imply a unique and stable solution to the model, very small movements in the parameter space often imply unstable solutions. In addition, the data prefer a *negative* estimate of Θ, in obvious contradiction to the theory. Thus I impose a Θ equal to the average capital share in income for the PDE capital stock over the sample. In fact, for the qualitative results presented below, it does not matter what value of Θ is imposed.

Interestingly, even when imposing linearity on the pattern of TTB weights (maintaining non-negativity and the sum to one constraint), the model is extremely sensitive to the value of the slope chosen. For example, at the estimated parameter values shown below, the model has no unique or stable solution for values of the slope less than .035 or greater than .106, although many values in this range satisfy the nonnegativity and sum constraints. I used a combination of grid search and conditional maximum likelihood (holding slope fixed while estimating adjustment cost parameters, and vice-versa) methods to find the optimal admissible slope and adjustment cost parameters. It is difficult to know the sampling properties of this method, but it was simply not possible to jointly estimate all the parameters and still satisfy the stability conditions for the model. The resulting estimates, presented below, imply a unique and stable solution for the model.[12]

I computed a numerical estimate of the Hessian (the second derivative of the log likelihood) at the final parameter values (still holding Θ at its imposed value). The results are summarized in the table below.

Table 2: Maximum Likelihood Estimates of TTB Investment Equation Parameters

Parameter	Max. Likelihood Estimate	Std. Error	t-stat.
s_k	0.037	0.0021	18.0
β	0.987	0.0365	27.0
α_1	140.423	14.2876	9.8
α_0	201.340	14.8935	13.5
	Implied TTB Weights		
ϕ_0	0.306		
ϕ_1	0.269		
ϕ_2	0.231		
ϕ_3	0.194		

Several comments on these estimates, and on the behavior of the model, are in order. First, judging by the time series properties of the structural residual, the model fits poorly. The Ljung-Box Q(12) statistic for the structural residual from the Euler equation has a p-value of .0014. Clearly, some important determinants of investment are missing, or some restrictions imposed by the model are grossly violated. The p-value for the likelihood ratio

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[12] Rouwenhorst (1991) discusses some difficulties that can arise in estimating the time-to-build parameters.

test for the restrictions imposed by this specification relative to the unconstrained linear model takes the value 0.

Second, the steps required to obtain a stable, unique set of parameter estimates casts additional suspicion on the usefulness of the TTB specification. Adding the Euler equation to an unconstrained VAR that summarizes the properties of the other variables in the system makes the system extremely fragile. For this reason, the system estimation that I have used here acts as an informative diagnostic tool for the model; one cannot arrive at parameter estimates without understanding their implications in the specification for the overall behavior of the model. Those who have estimated such models via GMM often do not have any way of knowing whether the "fit" of the model is reasonable, or whether the parameter estimates that they obtain imply a stable model. For example, the estimates for α_0, α_1, Θ, and the ϕs published in Oliner, Sichel, and Rudebusch imply a model with multiple solutions![13]

4 System Behavior of the Linear Model

I now combine the linear versions of the consumption and investment specifications with the linear price-contracting and reaction function equations to compare the implied interactions from the model with those evident in the data. The model thus comprises equations 1, 2, 4, 6, 9, and the reduced-form equations described in equations 11 and section 3.1. Note that, because

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[13] The model at their parameter values does not imply enough stability conditions to uniquely pin down the solution. Their model allows for a time-varying discount rate, but is otherwise identical. The maximum likelihood estimator used above imposes the root constraint as a nonlinear constraint on the parameters; a convergent estimate must lie in the feasible set and thus must satisfy the root constraints. GMM could, in principle, be augmented to include such a constraint, but standard practice does not do so.

I use the linear versions of the equations, there is still no direct link between consumption and investment, between the Fed's determination of the federal funds rate and real rates and investment, or between the sum of consumption and investment and real output. These links will be established in section 5 below.

Thus the question to be answered in this section is simply whether the partial-equilibrium estimates and linear versions of the consumption and investment sectors imply dynamics that are even approximately the same as those in the data. If this effort fails, die-hard fans of such specifications can hold on to the hope that the interactions omitted in this simplified specification will fix the problem in the next.

I compute the vector autocorrelation function of inflation, the federal funds rate, detrended consumption of nondurables and services (subtracting the trend in disposable income defined in equation 11), and the detrended investment-capital ratio for this model. I use the estimated parameter values reported in tables 1 and 2. The vector autocorrelation function is computed as described in Appendix A of Fuhrer and Moore (1995a).

For the sake of comparison, I estimate an eight-variable VAR in inflation, the funds rate, detrended investment, the detrended investment-capital ratio, the real after-tax price of investment goods, detrended per capita nondurables and services consumption, detrended real per capita disposable income, and detrended real per capita GDP. The Akaike and Schwarz-Bayes criteria suggest a lag length of 3, and the VAR is estimated from 1966:I to 1995:IV.

Figure 2 displays a comparison of the vector autocorrelation functions for the constrained (dashed lines) and unconstrained (solid lines) models. As the figure shows, the model correlations of consumption and investment with all other variables are acutely at odds with the correlations from the VAR.

The VAR exhibits a strong positive correlation between inflation and lagged consumption which the model reverses to a strong negative correlation. The same holds for the VAR prediction of a strong positive association between the funds rate and lagged consumption. The reverse-time correlations for consumption are just as bad: the VAR predicts a modest positive correlation between consumption and lagged inflation or funds rate, while the model predicts a very strong negative correlation.

As for investment, the situation is no better. Where the VAR implies positive correlations between lagged investment and inflation or the funds rate, the model implies a strong negative correlation. Investment's correlation with itself decays notably slower than indicated in the data.

A formal likelihood ratio test confirms the evidence presented in graphical form in the vector autocorrelation function. The log-likelihood difference between the constrained and unconstrained models is 2265.5. The p-value for the relevant χ^2 statistic takes the value 0.

Because no explicit interaction between consumption and investment, or between investment and inflation or the funds rate, is built in, perhaps we can explain away some of these poor correlations as the product of the incomplete linkages in the model. However, both consumption and investment depend on real income, which is linked via reduced-form equations to interest rates and inflation. To the extent that the reduced-form equations for real income capture the important dynamics in real income (and the VAR estimation results indicate that they do), at least *some* of the key correlations should be captured in this part-structural, part-reduced-form model. The results in Figure 2 are very discouraging in this regard.

Nonetheless, the possibility still exists that explicitly linking consumption and investment through their effects on real output, through the effects of the real rate on both, and through the feedback of output and real rates on investment and consumption, we can significantly improve some of the dynamic behavior of the model.

5 The "Complete" Nonlinear Model

As discussed in section 4, the linear model provides a convenient means of obtaining data-consistent parameter estimates, and some preliminary glimpses at the joint dynamic behavior of the key endogenous variables in the model. However, of necessity, a number of key linkages in the model are omitted. This section develops the full nonlinear version of the linear model and analyzes its behavior.

5.1 The Complete Specification

The additions to the model are as follows:

1. Investment and capital are now both endogenously determined. As a result, the investment-capital ratio, the output-capital ratio, and the square of the investment-capital ratio are all related to one another in the (nonlinear) way that they should be.

2. Also as a result of modeling the components of these ratios, investment is explicitly linked to the capital stock through the standard (time-to-build) accumulation identity, equation 11. Thus, in expectations of future capital, the link from today's investment to tomorrow's capital stock is explicitly exploited.

3. The discount rate is allowed to vary over time, and is determined as one over one plus the model-consistent expected real rate of interest, with duration equal to the estimated duration from the consumption sector (we will test robustness to this assumption below).

4. The real after-tax price of investment goods is modeled as an exogenous AR(1) process, estimated from the data:

$$p_t^I = .914 * p_{t-1}^I + 0.086$$

5. Real GDP is identically equal to the sum of nondurables and services consumption, equipment investment, and other GDP.

6. Other GDP is modeled as in Fuhrer and Moore (1995b), i.e. as a quasi-reduced-form IS curve:

$$Y_t^O = ((1 - .820) * \bar{Y}^O + 0.820 * Y_{t-1}^O - .270(\rho_t - \bar{\rho})$$

   The parameters for this equation are estimated using an *ex ante*, model-consistent real rate estimate from the F-M model.

7. Disposable personal income, y_t, is linked to real GDP, Y_t, via a simple error-correction equation:

$$y_t = .937 * Y_t + .752 * (y_{t-1} - Y_{t-1}) - 0.134$$

Appendix A lists the full set of equations and variable mnemonics for the complete model.

While the resulting model builds in most of the linkages in a fully fleshed out general equilibrium optimizing model, some important linkages are left out. The production function implicit in the investment equation does not determine potential output throughout. As noted above, there is no labor-leisure trade-off in the model, and labor does not enter as an input to production. Expenditures on consumer durable goods, investment in structures, and government and net exports are all subsumed in the other GDP variable.

5.2 Growth

The model is assumed to have a deterministic growth component. All the variables in the model described in this section are treated as deterministically detrended. This growth alternative requires two important adjustments to the consumption and investment equations, as shown in King, Plosser, and Rebelo (1988a).

1. The accumulation equation is altered to

$$(1 + \gamma_x)k_t = (1 - \delta_k)k_{t-1} + s_t \tag{13}$$

2. The time rate of preference δ in the consumption equation is altered to

$$\delta^* = \delta\gamma_x^{(1-\sigma)}$$

5.3 Steady-state

The detrended model implies the following steady-state:

5.4 Dynamic Correlations Implied By the Nonlinear Model

Figure 3 displays the vector autocorrelation function for the model. Because the model is nonlinear, the autocorrelation function does not summarize all of the information in the model likelihood, as it does for a linear model. Nonetheless, it provides a compact graphical summary of the important correlations in the model. The figure also plots the vector autocorrelation function for a VAR on the endogenous variables in the model as a summary of

Variable	Steady State Value[a]
Y	$\bar{Y}$
k	$\bar{Y}/\Omega$
i	$4(\gamma_x + \delta_k)k$
ρ	$\bar{\rho}$
β	$(1/(1+\rho))$
π	$\bar{\pi}$
f	$\bar{\pi} + \bar{\rho}$
p^I	1
y	$\log(((.937 - .752)\bar{Y})/(1 - .752) - 0.134/(1 - .752))$
yp	$(-\sigma/(1-\delta))\rho$
c	$y - ((1-\lambda)/(1-\delta))\sigma\rho - \mu$
Y^O	$\log(Y - i - \exp(c))$
Ω	$(1/(\Theta\beta^4))(\kappa - (\alpha_1/2)(\beta^4)(4(\gamma_x + \delta_k))^2)$
κ	$f(\phi_i; \beta, \gamma_x, \beta, \alpha_0, \alpha_1)$

[a] The constant κ in the steady-state expression for Ω, the steady-state output-capital ratio, is defined as

$$\kappa = [-(1+\alpha_0) - \alpha_1(4(\gamma_x + \delta_k))] \sum_{i=1}^{4} \phi_{i-1}((1-\delta_k)\beta^i - \beta^{i-1})$$

the properties of an unconstrained reduced-form model.[14] Because the autocorrelation functions are generated from repeated stochastic simulations, I also provide 90% confidence bands in the figure.

As the figure indicates, the model implies significantly different dynamic behavior for the four key variables indicated compared to the unconstrained model. Note that, as compared to the linearized version of the model examined in section 4, some of the dynamic correlations are improved by introducing the fuller set of simultaneities in this model. For example, the correlations between lagged consumption and lagged investment and inflation improve in Figure 3. In both cases, the initial positive correlation is likely understated by the structural model, but the understatement is noticeably less severe than in the linearized model. The same is true for the correspondingly "time-flipped" correlations between lagged inflation and consumption or investment.

However, the correlation between lagged consumption and current investment, while perhaps mildly improved over the linearized model, still is for the most part significantly different from the VAR's representation of the data correlation. In addition, the correlation between either consumption or investment and the federal funds rate, in either time direction, is completely at odds with the data. These correlations, which presumably reflect the reduced-form action of the monetary policy transmission channels in the model, are particularly disturbing. The funds rate in this model affects short-term real rates because of the persistence of the inflation rate, thus affecting the *ex ante* long-term real rate, thus altering consumption through intertemporal substitution, investment through the time-varying discount rate, and

---

[14] The vector autocorrelation function (VACF) cannot be computed analytically for this model. The VACF is computed from pseudo-data generated in two thousand stochastic simulations of the model, using the techniques described in Fuhrer and Bleakley (1996).

consumption and investment through direct and indirect output and disposable income effects. These effects should show up in the second row and column of the vector autocorrelation function. For consumption and investment, the structural model's correlations generally take the opposite sign of the data correlations. This seems a profound failure of the model.[15]

Perhaps equally disturbingly, the real side of the model has now seriously "contaminated" the money side of the model. The model-implied correlation between the lagged funds rate and inflation, the second column in the first row of panels, appears completely at odds with the VAR's estimate of the same correlation. In the VAR (and the original F-M specification), higher-than-average lagged funds rates are followed 6 to 10 quarters later by lower than average inflation. The correlation for the first year or two is positive. In the nonlinear structural model, the correlation between the lagged funds rate and inflation turns strongly negative *immediately*. The VAR's correlations for this panel lie outside the 90% confidence intervals for the nonlinear model's estimated correlation. This behavior likely arises from the perverse-signed correlations between the funds rate and real activity described above; because inflation in the contracting specification is affected by real activity, the backwards funds rate-output correlations imply backwards funds rate-inflation correlations. Note that this problem carries over to the correlation between lagged inflation and the funds rate as well, although in less dramatic fashion.

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[15] The reduced-form process for the real after-tax price of investment goods, while consistent with the data, suggests considerable persistence in that price. While this persistence may reflect either inherent "stickiness" in the price, or the apparent persistence that arises from a set of persistent real adjustments that impart persistence to this relative price, it may be informative to test the robustness of the qualitative features of the autocorrelation function to this assumption. I alternatively model the investment price as completely flexible from period to period (although with a long-run equilibrium value to which it must ultimately return). Changing this assumption yields no discernable change in the vector autocorrelation function.

Overall, then, while the fully simultaneous model yields some modest improvements in the reduced-form correlations between real variables in inflation, it does so at the expense of other key correlations in the model. The reduced-form implications of the monetary transmission mechanism are inconsistent with the data. This observation, together with the shortcomings of the consumption and investment specifications described above, sounds the death knell of this model.

5.5 Disinflation simulations

The strength of the vector autocorrelation function is that equivalent information for identified and unidentified (reduced-form) models can be compared. The weakness is that it is more difficult to place structural interpretations on the correlations (although a modest attempt is made to do so above).

To sort out the structural sources of the perverse correlations uncovered in the previous section, I look at a simple disinflation simulation of the complete nonlinear model. The disinflation sets the initial conditions for the model at the steady state with an inflation target and steady-state inflation rate of 3 percent. At the beginning of the simulation, the inflation target is lowered to 0, and the new inflation target is known from that point forward. The new equilibrium federal funds rate is 5 percent, and all other steady-state values remain as before.

The results of the simulation, displayed in Figure 4, provide a structural interpretation of the dynamic correlations in the VACF. In essence, consumption and investment behave like jump variables (such as the purely forward-looking long-term real rate, for example), pulling all future movements in income and rates back to the onset of the disinflation. This implies that movements in the funds rate have their maximal effect on real output and inflation immediately, diminishing thereafter. The correlations in the data are consistent with a different dynamic: when the funds rate is raised, the initial effects are small, and they reach their maximum some eight quarters later. Because the structural model shifts the response of real variables dramatically backward in time, the model cannot accurately replicate these important correlations in the data. The monetary transmission mechanism (from rates to real spending to inflation), while moving in the right direction, does so much too quickly.

5.6 Full Information Estimates of the Nonlinear Model

As a final check on the results presented above, I estimate the full nonlinear model with a full-information maximum likelihood estimator described in Fuhrer and Bleakley (1996). This is a computationally burdensome undertaking: even though a single solution of the model requires about one second, each step in improving the likelihood requires at least $T \times n_\theta$ solutions, where T is the sample size and n_θ is the number of parameters. For this model and dataset, $T = 120$ and $n_\theta = 15$, so that each step takes about 30 minutes of CPU time.

The results of the estimation are presented in table 3 below. As the table indicates, the parameters differ somewhat from those estimated for the linear versions of the specification. However, as Figure 5 shows, the vector autocorrelation function implied by the model at these parameter estimates is nearly identical to the VACF computed at the initial parameter estimates.

6 Conclusions

A growing body of work incorporates sticky-price models in an optimizing framework. The motivation for this research comes from two sources. First,

Table 3: Full-Information Maximum Likelihood Estimates of the Model

Parameter	Nonlinear Model Estimate	Linear Model Estimate
s_k	0.037	(constrained)
α_π	0.425	-
$\bar{\pi}$	0.036	-
α_y	0.425	-
α_1	80.120	96.458
Θ	0.340	(constrained)
α_0	12.0	8.715
λ	0.540	0.4751
μ	0.204	-
σ	0.167	0.1780
δ	0.506	0.5280
$\bar{\rho}$	0.055	-
d	4.208	3.7807
	Implied TTB Weights	
ϕ_0	0.306	0.306
ϕ_1	0.269	0.269
ϕ_2	0.231	0.231
ϕ_3	0.194	0.194

a substantial branch of empirical work concludes that wages and prices are sticky; this evidence forms the basis for a near-consensus in the profession. Second, it is now widely recognized that standard optimizing models with flexible prices imply severely counter-factual dynamics for many variables of interest. Hence, one hope for optimizing models is that the inclusion of sticky prices will correct some of the deficiencies that arise in the flexible-price models.

This paper provides some evidence that this hope is not well-founded, at least not for models that rely on contracting to induce price rigidities. It remains an open question, of course, whether different investment specifications–perhaps the recent contributions of Abel and Eberly (1995) or Caballero and Engel (1994), for example–could attain greater empirical success when coupled with a sticky price specification. It is also possible that the sticky price models that arise from the assumption of imperfect competition could perform better than the contract-based model used here.

However, the results presented here may help in sorting among competing real-side specifications. First, on the consumer side, I reinforce the notion that predictable changes in contemporaneous income are important in explaining changes in consumer expenditures, as in Campbell and Mankiw. However, the overall results for a fairly standard specification of life-cycle consumers are decidedly discouraging. The data cannot strongly discriminate between the case in which a very small fraction of income accrues to consumers who are significantly forward-looking and the case in which a sizable fraction of income accrues to consumers who are forward-looking, but only slightly. These results suggest that a successful model of consumer behavior must rationalize a very short planning horizon or a very high discount rate or both.

Second, on the investment side, the neoclassical-style investment models, whether augmented to include time-to-build and costs of adjustment or not, seem doomed to fail. The adjustment costs required to smooth the response of investment to shocks to the real price of investment goods or to expected output are implausibly large. Yet, even at the huge estimated values of the adjustment cost parameters, the model cannot capture investment's persistent correlations displayed in the data, either with its own past or with lags of other key variables.

Finally, the results presented above suggest that the sum of real expenditures must respond somewhat sluggishly to changes in the short-term interest rate If not, some fundamental dynamic correlations in the data will be trampled upon. If the Fed can systematically alter the short-term rate so as to affect expectations of the path of future short-term real rates, and if the bond market discounts future real rate movements back to the present, then the sluggish response must come from the behavior of real expenditures. Most (if not all) of the optimizing models in the literature suggest immediate responses of investment and consumption to changes in the real rate, in strong contradiction to the data. The success of the quasi-reduced-form IS curve in the original F-M specification (which included the same description of policy and the bond market) derives from its ability to neatly capture this feature of the data.

Appendix A: Model Equations and Variable Mnemonics

Variable Definitions

Mnemonic	Variable
π	Inflation rate
x	Log contract price
p	Log price index
v	Real contract price index
f	Federal funds rate
k	Stock of producers' durable equipment
i	Investment in PDE
S	Starts (TTB specification)
β	Discount factor
p^I	Real, after-tax price of investment goods
c	Nondurables and service consumption
y	Disposable income
Y	Real GDP
Y^O	Other GDP
ρ	*Ex ante* real interest rate

Equation Specifications

$$\pi_t = 4.0(p_t - p_{t-1})$$

$$x_t - p_t = \sum_{i=0}^{3} \omega_i (v_{t+i} + \gamma(Y_{t+i} - \bar{Y}))$$

$$p_t = \sum_{i=0}^{3} \omega_i x_{t-i}$$

$$v_t = \sum_{i=0}^{3} \omega_i (x_{t-i} - p_{t-i})$$

$$f_t - f_{t-1} = a_\pi(\pi_t - \bar{\pi}) + a_y \log(Y_t/\bar{Y})$$

$$(1 + \gamma_x)k_t = (1 - \delta_k)k_{t-1} + 0.25S_{t-3}$$

$$\begin{aligned}
&\sum_{i=0}^{3} \phi_i[(1 - \delta_k)p^I_{t+i+1}\beta^*_{t,i+1} - p^I_{t+i}\beta^*_{t,i}] \\
&+\alpha_1((i_{t+4}/k_{t+3})^2(\beta^*_{i,4}/2)) \\
&+\alpha_1 \sum_{i=0}^{3}[\phi_i((1 - \delta_k)\beta^*_{t,i+1}(i_{t+i+1}/k_{t+i}) - \beta^*_{t,i}(i_{t+i}/k_{t+i-1}))] \\
&+\Theta((Y_{t+4}/k_{t+3})\beta^*_{t,4}) \\
&+\alpha_0 \sum_{i=0}^{3}[\phi_i((1 - \delta_k)\beta^*_{t,i+1} - \beta^*_{t,i})]
\end{aligned}$$

$$\beta^*_{t,s} = \prod_{j=0}^{s} \beta_{t+j} \; ; \; \beta_{t,0} = 1$$

$$\beta_t = (1/(1+\rho_t))$$

$$p_t^I = .914 p_{t-1}^I + 0.086$$

$$c_t = y_t + (1-\lambda) y_t^p - \mu$$

$$y_{t+1} - y_t - \sigma \rho_t = y_t^p - \delta y_{t+1}^p$$

$$Y_t = \exp(Y_t^O) + \exp(c_t) + i_t$$

$$\exp(y_t) = .937 Y_t + 0.752(\exp(y_{t-1}) - Y_{t-1}) - 0.134$$

$$Y_t^O = (1 - .81977)\log(\bar{c}) + 0.81977 Y_{t-1}^O - .26971(\rho_t - \bar{\rho})$$

$$f_t - \pi_{t+1} = \rho_t - D(\rho_{t+1} - \rho_t)$$

$$i_t = \phi_0 S_t + \phi_1 S_{t-1} + \phi_2 S_{t-2} + \phi_3 S_{t-3}$$

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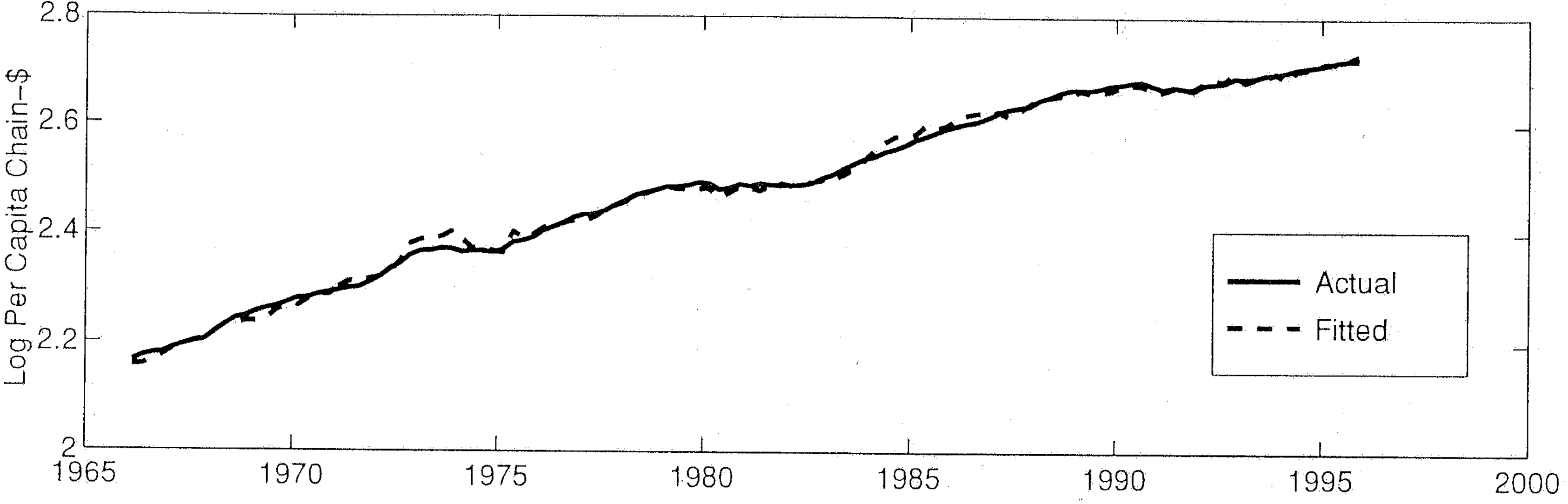
Figure 1

Fit vs. Actuals

Consumption Model

Consumption Levels



Consumption Growth Rates

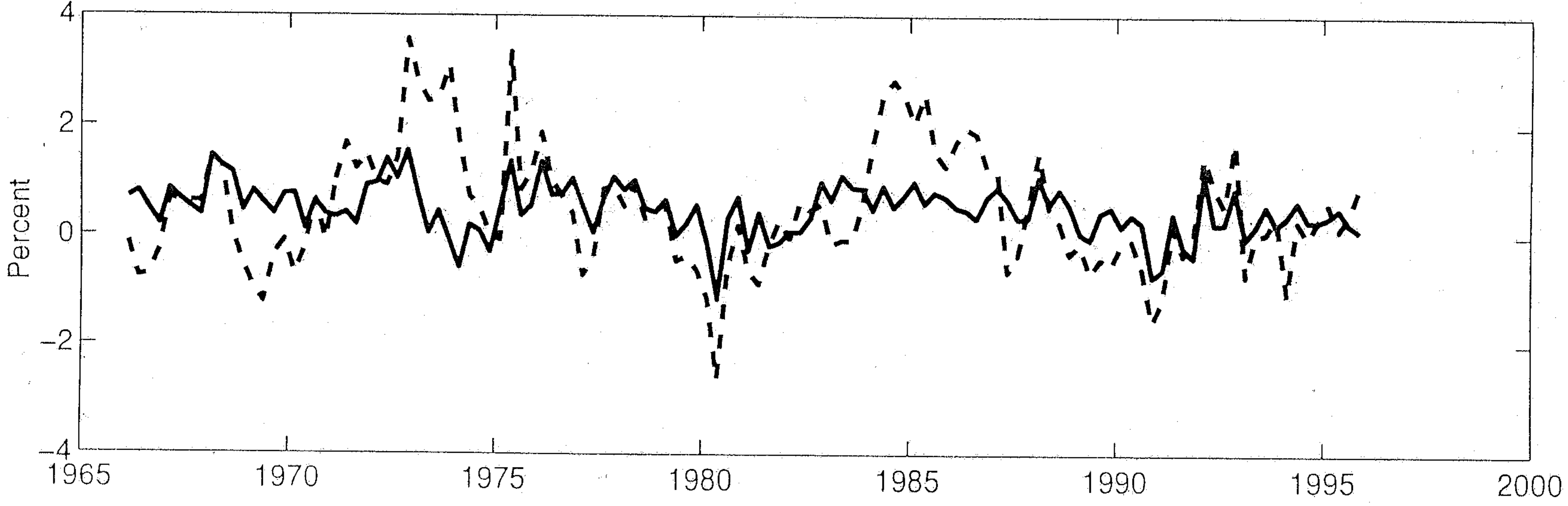
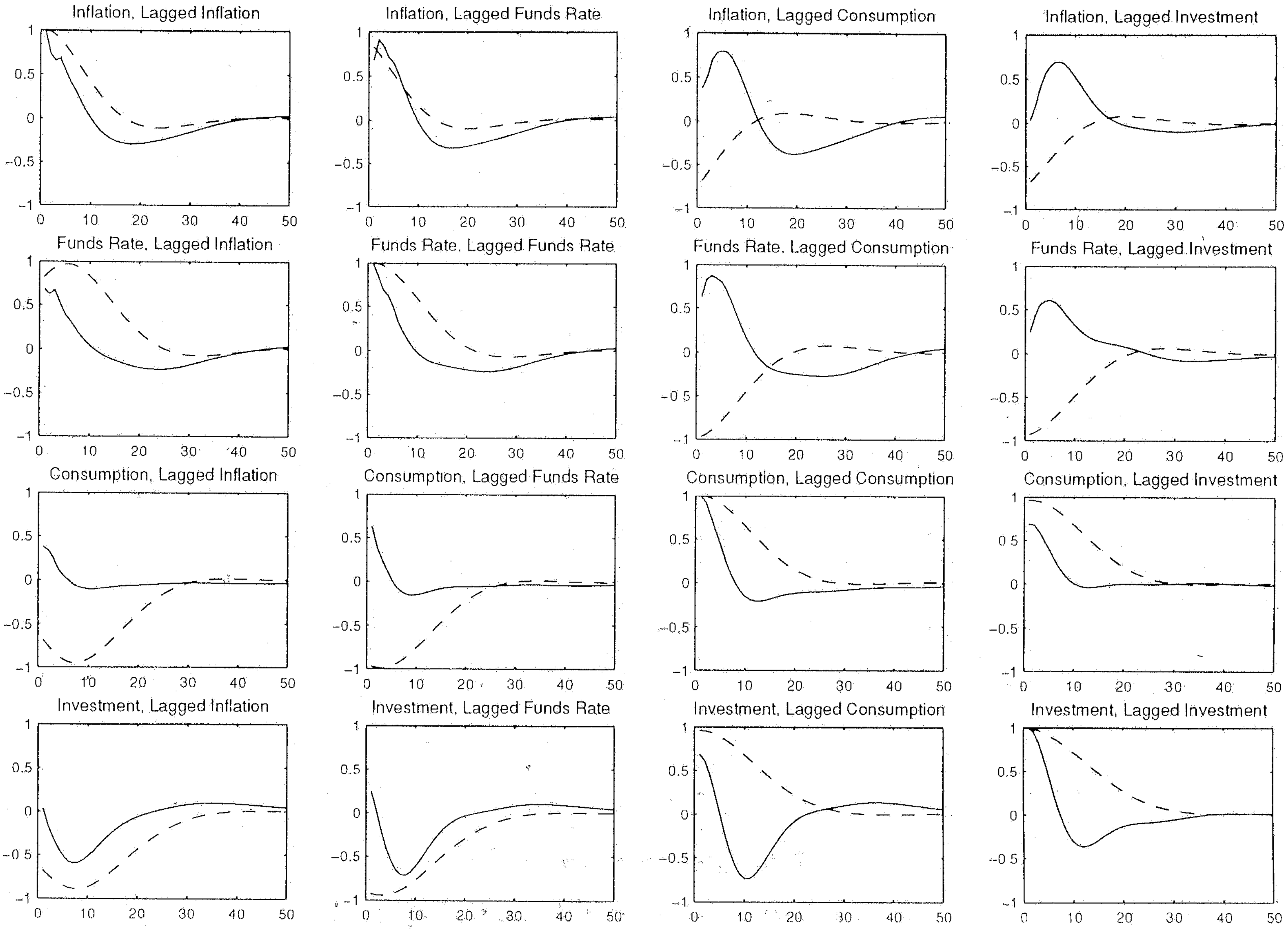


Figure 2

Comparison of Autocorrelation Functions

Linear TTB and Consumption model vs. VAR

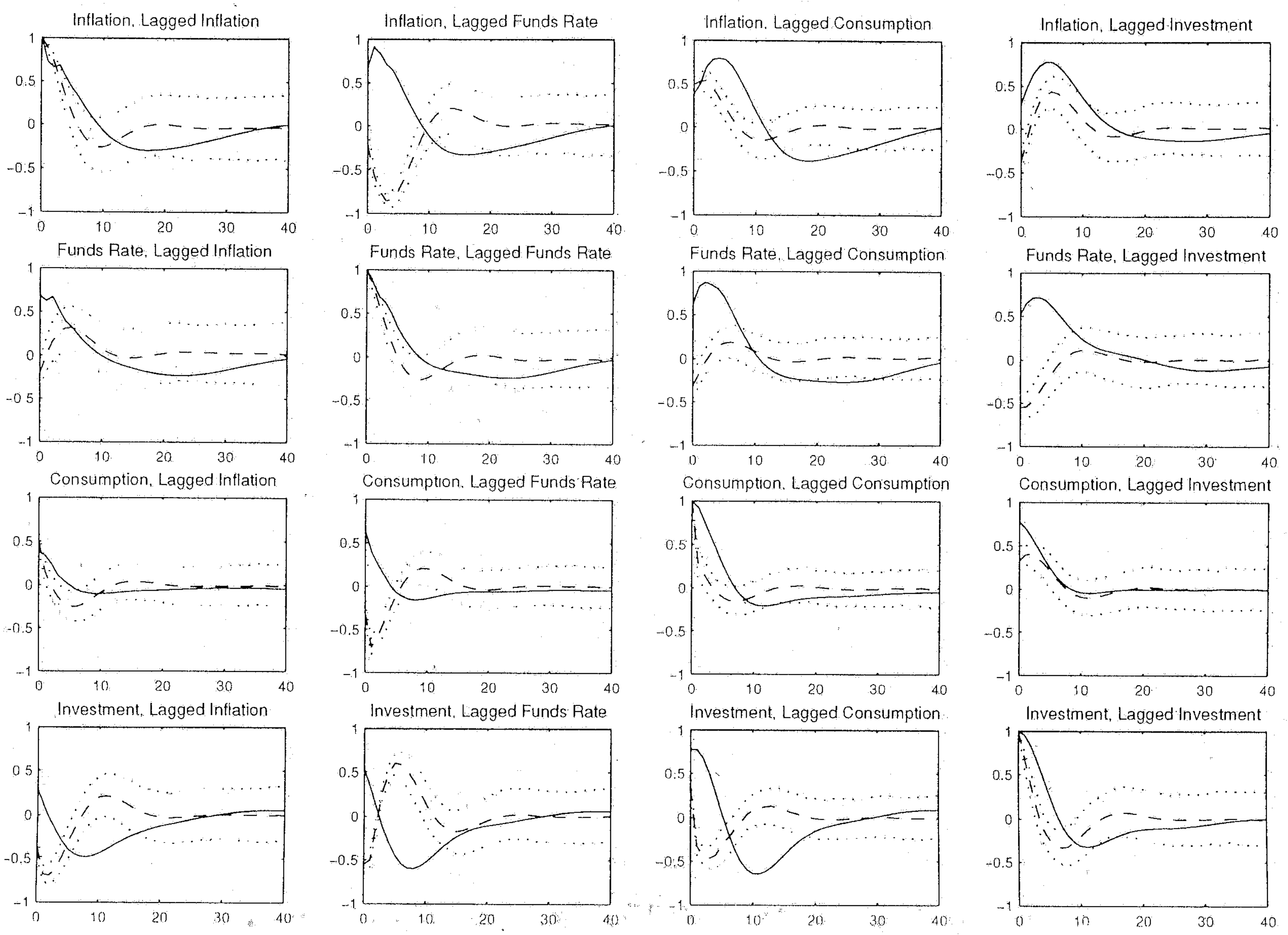


Solid line, VAR, dashed line, linear model

Figure 3

Autocorrelation Functions

Nonlinear and VAR models

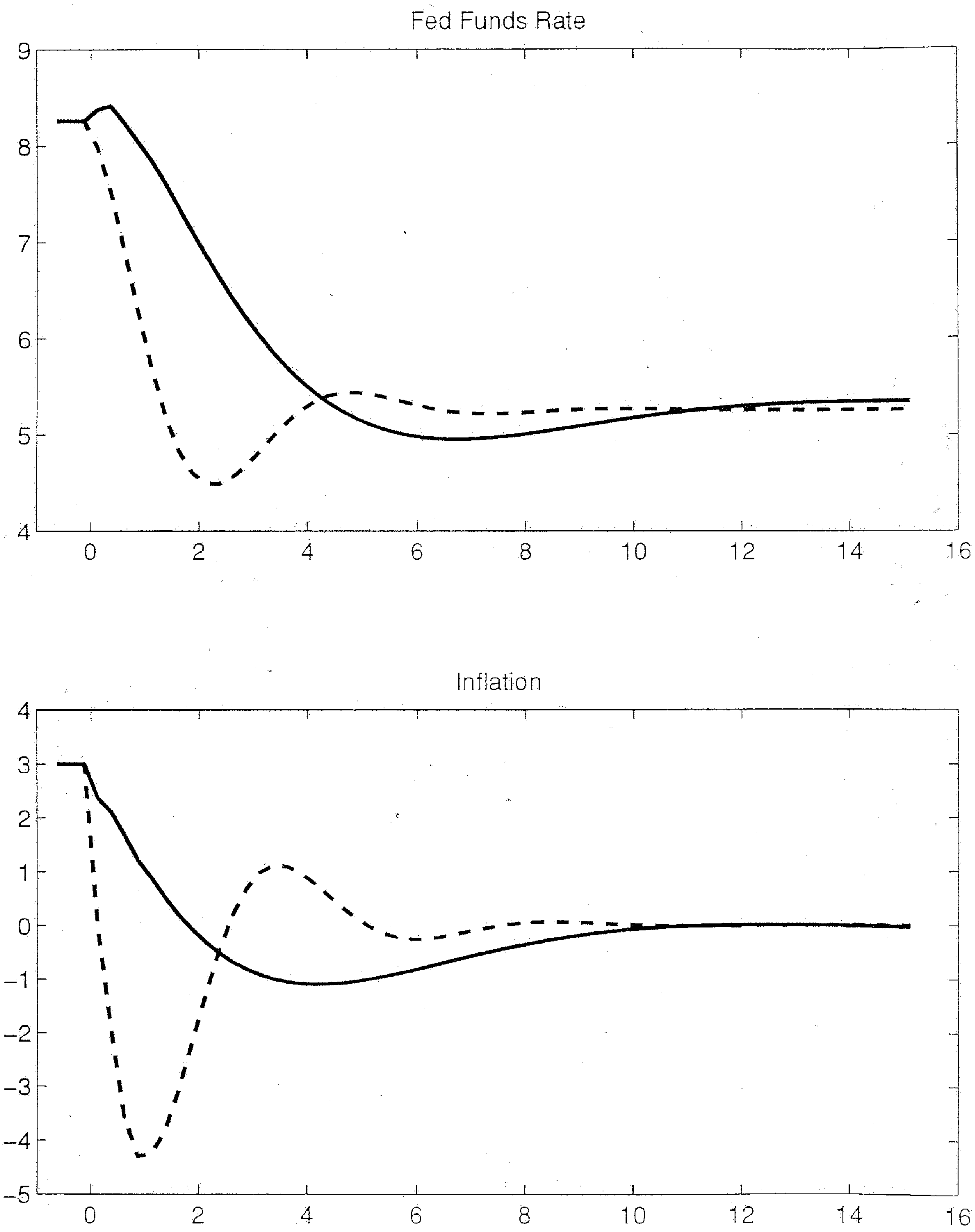


Solid line, VAR; dashed line, nonlinear model; dotted lines, 90% confidence bands for nonlinear model

Figure 4

Disinflation Simulation

Nonlinear TTB vs. Fuhrer-Moore Model

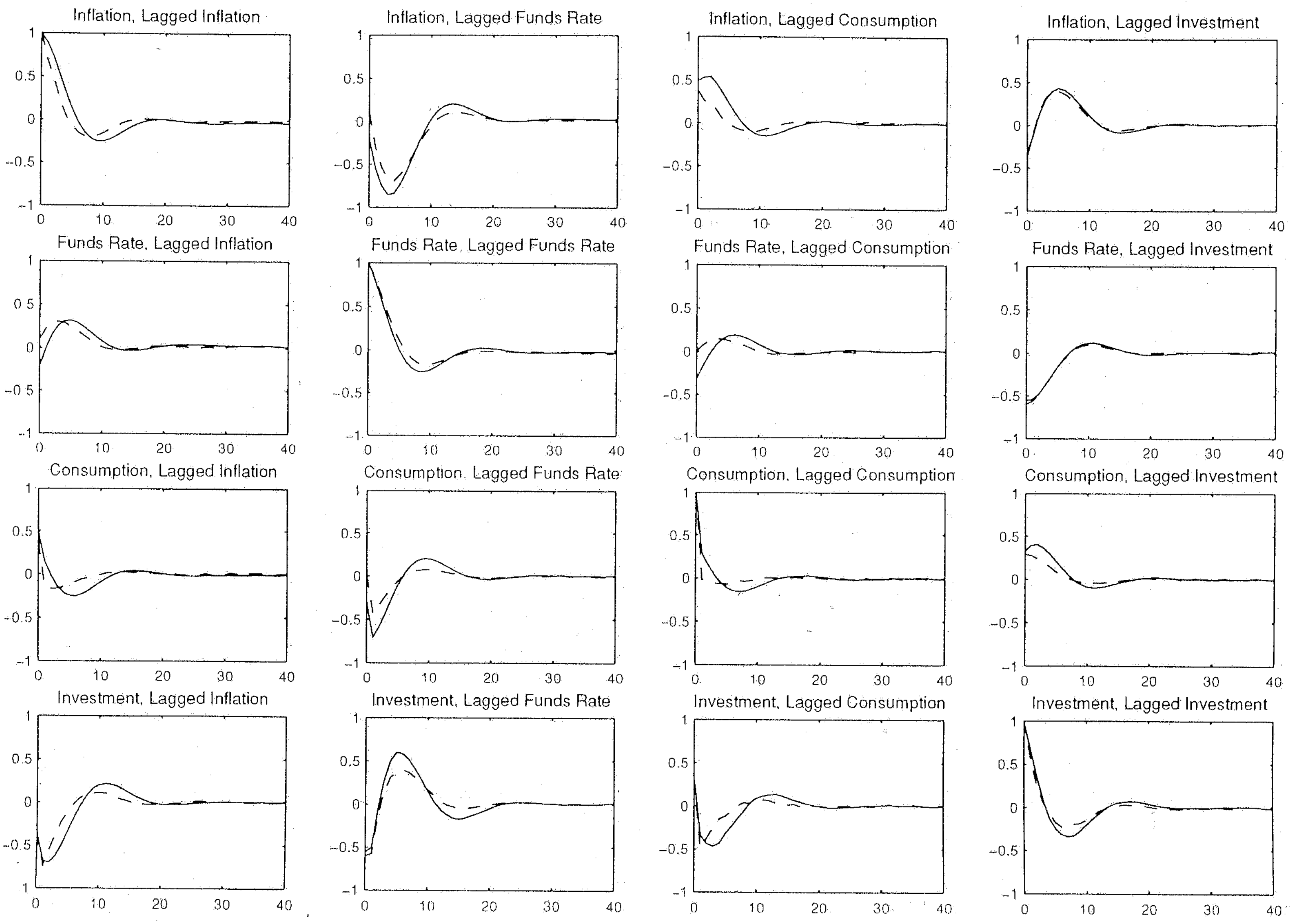


Solid line, Fuhrer–Moore; dashed line nonlinear time–to–build model

Figure 5

Autocorrelation Functions

Sensitivity to Parameter Estimates



Solid line: Mean ACFs using parameters estimated from the linear model

Dashed line: Mean ACFs using parameters estimated from the nonlinear model

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