

# LUMPY DURABLE CONSUMPTION DEMAND AND THE LIMITED AMMUNITION OF MONETARY POLICY

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The prevailing neo-Wicksellian view holds that the central bank's objective is to track the natural rate of interest ( $r^*$ ), which itself is largely exogenous to monetary policy. We challenge this view using a fixed-cost model of durable consumption demand, in which expansionary monetary policy prompts households to accelerate purchases of durable goods. This yields an intertemporal trade-off in aggregate demand as encouraging households to increase durable holdings today leaves fewer households acquiring durables going forward. Interest rates must be kept low to support demand going forward, so accommodative monetary policy today reduces  $r^*$  in the future. We show that this mechanism is quantitatively important in explaining the persistently low level of real interest rates and  $r^*$  after the Great Recession.

KEYWORDS: Monetary policy, durable goods, interest rates.

## 1. INTRODUCTION

WHEN ENTERING A RECESSION, the first tool in the arsenal of macroeconomic policymakers is to lower interest rates. Lower real interest rates encourage businesses to invest and consumers to spend, which bolsters aggregate demand. An important component of this monetary transmission mechanism is to stimulate purchases of durable goods, which are particularly sensitive to interest rates (e.g., Barsky, House, and Kimball (2003), Erceg and Levin (2006), Sterk and Tenreyro (2018)). In this paper, we argue that stimulating demand for durable goods has additional consequences. As monetary stimulus increases the stock of durables today, there is less need to acquire durable goods in the future, all else equal. Monetary policy therefore raises aggregate demand today by borrowing demand from the future. To compensate for the weakness in aggregate demand going forward, the central bank must keep real interest rates low. That is, monetary policy stimulus has a side effect of reducing the real natural rate of interest ( $r^*$ ) in subsequent periods.

This interaction between monetary policy and  $r^*$  is very different from the prevailing neo-Wicksellian view (Woodford (2003)) that  $r^*$  is largely exogenous to monetary policy

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We are grateful to Adrien Auclert, Robert Barsky, David Berger, Jeff Campbell, Adam Guren, Jim Hamilton, Christopher House, Rohan Kekre, Emi Nakamura, Valerie Ramey, Matthew Rognlie, Jón Steinsson, Ludwig Straub, Stephen Terry, Joe Vavra, Venky Venkateswaran, Tom Winberry, Christian Wolf, and seminar participants at Boston University, University of Michigan, Harvard University, the Federal Reserve Banks of Boston, Minneapolis, San Francisco, and St. Louis, the 2019 ASSA meetings, U.C. Berkeley, Chicago Booth, LSE, IIES, SED 2019, and the NBER Summer Institute (ME 2019, EF&G 2020). Charles Fries provided excellent research assistance. Wieland is grateful to the Federal Reserve Bank of Chicago for its hospitality while completing parts of this paper. The views expressed here are those of the authors and do not necessarily reflect the position of the Federal Reserve Bank of Minneapolis, the Federal Reserve Bank of Chicago, or the Federal Reserve System.

and the central bank aims to manipulate the policy rate to track  $r^*$ .<sup>1</sup> In contrast, we argue that monetary policy has a powerful impact on the future evolution of  $r^*$  through the intertemporal shifting of aggregate demand.

We show that this intertemporal shifting is an important piece of the monetary transmission mechanism in a heterogeneous agent New Keynesian model in which households accumulate durable consumption goods subject to fixed adjustment costs. Households optimally follow an (S,s) policy, making lumpy durable purchases as their existing durable stock drifts down and hits an adjustment threshold. Expansionary monetary policy shifts the adjustment thresholds, accelerating adjustments by those who were close to an adjustment threshold. For instance, low interest rates may prompt some households to accelerate the purchase of a new car. In the subsequent periods, they no longer need to purchase a car as they have already done so. As a result, aggregate demand is weaker in periods following the stimulus.

The dynamics of demand for durable goods create a propagation mechanism that makes changes in real interest rates very persistent. We use our model to construct a forecast for the evolution of interest rates following the Great Recession, in which the Federal Reserve engaged in massive countercyclical monetary stimulus. Based on information through 2012Q4, our model predicts a path of interest rates that largely tracks the path that came to pass over the next 7 years. The model predicts liftoff from the effective lower bound (ELB) in 2015Q4 and predicts low levels of interest rates in 2019Q4 just as in the data. The slow normalization of interest rates reflects a persistent decline in  $r^*$ . We isolate the contribution of intertemporal shifting to the path of  $r^*$  and show that it is quantitatively important to explaining the large drop and, especially, the slow normalization of  $r^*$ .

In recent years, the low level of interest rates has received a lot of attention (Summers (2015), Laubach and Williams (2016)). These low rates are generally thought to reflect secular phenomena such as demographic changes, slow trend productivity growth, an increasing convenience yield for safe assets, and the rise in income inequality (Eggertsson, Mehrotra, and Robbins (2019), Del Negro, Giannone, Giannoni, and Tambalotti (2017), Auclert and Rognlie (2018), Straub (2019)). Our results demonstrate that cyclical forces can have large and very persistent effects on the natural rate of interest, and that these forces have contributed substantially to the low interest rates over the last decade. However, our perspective is fully compatible with the view that secular phenomena have played a role in the decline in interest rates over a longer time horizon.

A fixed-cost model is a natural modeling approach to capture the lumpiness of durable adjustments in the microdata. However, the nature of the adjustment costs we include in our model is also central to our main findings. The logic of our argument can actually be reversed in models with higher-order adjustment costs, a common formulation in which adjustment costs are increasing in the rate of change of investment (e.g., Christiano, Eichenbaum, and Evans (2005)). With higher-order adjustment costs, low interest rates today stimulate investment today, which lowers the marginal cost of investment in the future. This effect works against the intertemporal shifting effect we highlight, whereby higher investment today increases the future durable stock, which reduces marginal benefit from investing in the future. Thus, if higher-order adjustment costs are large enough,

<sup>1</sup>See Woodford (2003, p. 49): “In Wicksell’s view, price stability depended on keeping the interest rate controlled by the central bank in line with the natural rate determined by real factors (such as the marginal product of capital). [...] Wicksell’s approach is a particularly congenial one for thinking about our present circumstances [...]”

low interest rates today may even raise future aggregate demand. Higher-order adjustment costs help DSGE models to match certain features of the aggregate response of durable demand to interest rates. However, they are at odds with the microdata that shows lumpy adjustments in consumer durables and business investment.

We show that our model is consistent with both the adjustment process at the microlevel and the aggregate response of durable demand to interest rates. In particular, we show that the impulse response of aggregate durable spending to a monetary policy shock is similar to what we estimate using the [Romer and Romer \(2004\)](#) shocks. Notably, our estimates for the responses of GDP, aggregate durable expenditure, and the extensive margins of car and housing adjustments all show reversals consistent with intertemporal shifting. While the extent of these reversals is not precisely estimated, in most cases the point estimates show complete reversals with the cumulative change in activity eventually returning to zero. Turning to cross-sectional evidence, anticipated changes in sales tax rates create incentives for intertemporal substitution similar to changes in interest rates ([Correia, Farhi, Nicolini, and Teles \(2013\)](#)). We exploit this observation to make use of cross-sectional evidence from [Baker, Kueng, McGranahan, and Melzer \(2019\)](#) on the response of auto sales to anticipated sales tax changes at the state level. Again, the response of auto sales shows a clear reversal with cumulative sales returning to zero shortly after the sales tax change. Our model tracks this impulse response quite closely.

The timing of durable purchases in standard fixed-cost models is highly sensitive to intertemporal incentives (see [House \(2014\)](#)). [Reiter, Sveen, and Weinke \(2013\)](#) argue that this property implies a counterfactually large investment response to monetary stimulus in a New Keynesian model extended with a relatively standard (S,s) model of investment demand. We show that including two particular ingredients in our model is important to match the empirical evidence mentioned above. Without these ingredients, the model-implied response of durable demand to interest rates is an order of magnitude larger than our empirical benchmarks. First, operating costs are a component of the user cost of durables that is not sensitive to interest rates, which limits the shift in the (S,s) adjustment thresholds. Second, shocks to the quality of the match between a household and its durable stock introduce inframarginal adjustments, which reduce the mass of households near the adjustment thresholds. We use microdata on durable adjustments to estimate the frequency of match-quality shocks. Our model also includes information rigidities in the style of [Carroll, Crawley, Slacalek, Tokunaka, and White \(2020\)](#). This friction helps the model match the delayed responses to monetary policy shocks that are often observed in aggregate data, as shown by [Auclert, Rognlie, and Straub \(2020\)](#).

Our work builds on a growing literature that models aggregate demand using rich micro-foundations for household consumption that are disciplined by microdata.<sup>2</sup> Most of this literature focuses its attention on the determination of nondurable consumption and abstracts from consumer durables. Our interest in durable goods is motivated by the fact that they are more sensitive to monetary policy and more cyclical than nondurable consumption. Our partial-equilibrium household decision problem builds on [Berger and Vavra \(2015\)](#) adding match-quality shocks and operating costs to lower the interest elasticity of durable demand, as well as sticky information to delay the demand response, so that both are in line with our empirical benchmarks.

Our analysis is made possible by the recent advances in the computation of heterogeneous agent macro models, specifically we make use of and extend the powerful sequence-

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<sup>2</sup>See [Guerrieri and Lorenzoni \(2017\)](#), [McKay and Reis \(2016\)](#), [Gornemann, Kuester, and Nakajima \(2016\)](#), [McKay, Nakamura, and Steinsson \(2016\)](#), [Auclert \(2019\)](#), [Kaplan, Moll, and Violante \(2018\)](#), [Werning \(2015\)](#) among others.

space Jacobian techniques developed by Auclert, Bardóczy, Rognlie, and Straub (2021). We make two technical contributions. We show how to implement the Kalman filter to recover the shocks that generated the aggregate time series data using only impulse response functions and not relying on a state space representation of the model. We then extend this filtering algorithm to incorporate the ELB constraint, by allowing for a sequence of anticipated monetary news shocks. Second, we show how  $r^*$  can be immediately calculated from the impulse response functions of the model without solving an auxiliary flexible-price model as is typically done in DSGE models.

Intertemporal shifting effects of monetary policy have appeared in the literature previously. Leamer (2007, 2009) informally argues that monetary policymakers should take account of intertemporal shifting effects in housing. Kreamer (2019) showed that minimizing inefficient sectoral fluctuations in a stylized model of durable demand requires monetary policy to take into account intertemporal shifting effects. Our contribution is to provide evidence of intertemporal shifting effects, quantify them in a rich model disciplined by micro and macrodata, and examine its positive implications for the dynamics of real interest rates.

Contemporaneous work by Mian, Straub, and Sufi (2020) argues that intertemporal shifting of demand can also occur following monetary accommodation due to the accumulation of household debt. The mechanism we focus on is a different one. To illustrate the difference, nonhomothetic preferences are central to the mechanism described by Mian, Straub, and Sufi so that the reduction in demand from indebted households is not offset by an increase in demand from their creditors. In contrast, our mechanism works through durable holdings with homothetic preferences.

A recent strand of literature has analyzed how past interest rates affect the power of monetary policy through mortgage refinancing decisions (Berger, Milbradt, Tourre, and Vavra (2018), Eichenbaum, Rebelo, and Wong (2018)). With fixed-rate mortgages, an interest rate cut is more powerful in spurring refinancing and stimulating the economy if interest rates have been high in the past and homeowners have high rates on their existing mortgages. The refinancing mechanism studied by these papers does not cause the intertemporal shifting of demand that we focus on. Intertemporal shifting implies that monetary stimulus today increases aggregate demand today and lowers demand in the future. The refinancing channel implies that monetary stimulus increases demand both now and in the future, but future demand becomes less sensitive to any future change in monetary policy.

The paper is organized as follows: Section 2 presents our model of durable demand; Section 3 shows that the model aligns with the evidence on the response of durable spending and output to changes in real interest rates, discusses the empirical evidence for intertemporal shifting effects, and explains the roles of match-quality shocks and operating costs; Section 4 describes the general equilibrium model with sticky wages; Section 5 documents the intertemporal shifting implications for the monetary transmission mechanism; Section 6 shows that this feature of the monetary transmission mechanism has important implications for the dynamics of interest rates during and after the Great Recession; Section 7 concludes.

## 2. MODEL OF DURABLE DEMAND

We begin with the household's partial equilibrium decision problem, which forms the demand side of the model. Later we will embed this demand block into a sticky-wage monetary model.

### 2.1. Household's Problem

Households consume nondurable goods,  $c$ , and a service flow from durable goods,  $s$ . Household  $i \in [0, 1]$  has preferences given by

$$E_{i0} \int_{t=0}^{\infty} e^{-\rho t} u(c_{it}, s_{it}) dt.$$

The service flow from durables is generated from the household's stock of durable goods  $d_{it}$ . For the most part, we have  $s_{it} = d_{it}$ , but we will complicate this relationship below. The expectation is individual-specific due to information frictions, which we also describe below.

Households hold a portfolio of durables and liquid assets denoted  $a_{it}$ . When a household with preexisting portfolio  $(a_{it}, d_{it})$  adjusts its durable stock, it reshuffles its portfolio to  $(a'_{it}, d'_{it})$  subject to the payment of a fixed cost such that

$$a'_{it} + p_t d'_{it} = a_{it} + (1 - f) p_t d_{it},$$

where  $p_t$  is the relative price of durable goods in terms of nondurable goods, and  $f p_t d_{it}$  is a fixed cost proportional to the value of the durable stock. Liquid savings pay a safe real interest rate  $r_t$ . The household is able to borrow against the value of the durable stock up to a loan-to-value (LTV) limit  $\lambda$ ,

$$a_{it} \geq -\lambda(1 - f) p_t d_{it}.$$

Borrowers pay real interest rate  $r_t + r_t^b$ , where  $r_t^b$  is an exogenous borrowing spread.

The stock of durables depreciates at rate  $\delta$ . Following [Bachmann, Caballero, and Engel \(2013\)](#), a fraction  $\chi$  of depreciation must be paid immediately in the form of maintenance expenditures. This maintenance reduces the drift rate of the durable stock so we have

$$\dot{d}_{it} = -(1 - \chi)\delta d_{it},$$

where a dot over a variable indicates a time derivative. The household must also pay a flow cost of operating the durable stock equal to  $\nu d_{it}$ . Broadly speaking, these operating costs reflect expenditures such as fuel, utilities, and taxes.

When a household does not adjust its durable stock, its liquid assets evolve according to

$$\dot{a}_{it} = r_t a_{it} + r_t^b a_{it} I_{\{a_{it} < 0\}} - c_{it} + y_{it} - (\chi\delta p_t + \nu) d_{it}.$$

Household income,  $y_{it}$ , is given by  $y_{it} = Y_t z_{it}$ , where  $Y_t$  is aggregate income and  $z_{it}$  is the household's idiosyncratic income share, which we later interpret as idiosyncratic labor productivity.  $\ln z_{it}$  follows the Ornstein–Uhlenbeck process

$$d \ln z_{it} = -\rho_z (\ln z_{it} - \ln \bar{z}) dt + \sigma_z d\mathcal{W}_{it}^z,$$

where  $d\mathcal{W}_{it}^z$  is a standard Brownian motion,  $\rho_z$  controls the degree of mean reversion of the income process,  $\sigma_z$  determines the variance of the income process, and  $\bar{z}$  is a constant such that  $\int z_{it} di = 1$ .

We allow for the possibility that households may occasionally adjust their durables because their existing durables are no longer a good match for them. These match-quality

shocks are meant to capture unmodeled life events that leave the household wanting to adjust for reasons other than income fluctuations and depreciation. For example, a job offer in a distant city may prompt the household to move houses. Or a growing family may require a larger car. We assume that a household is in a good match when it adjusts its durables, but over time the match quality can break down according to a Poisson process with intensity  $\theta$ . Specifically, there is a state  $q_{it}$  that takes a value 1 when the household adjusts its durables and drops to zero with intensity  $\theta$ . The service flow is  $s_{it} = q_{it}d_{it}$ . In equilibrium, households with bad matches will adjust their durable stocks immediately. These match-quality shocks are therefore a source of inframarginal adjustments.

Households have incomplete information about the aggregate state of the economy as in [Mankiw and Reis \(2002\)](#). Each household updates its information with Poisson intensity  $\Xi$ . As in [Carroll et al. \(2020\)](#) and [Auclert, Rognlie, and Straub \(2020\)](#), we assume that households always know their idiosyncratic states and current income. They also learn the current real interest rate when they hit the borrowing constraint and they learn the current price of durables when they make an adjustment. These assumptions ensure that households never violate the borrowing constraint. These information frictions allow the model to generate the hump-shaped response of durable and nondurable expenditure to monetary shocks.

## 2.2. Distribution and Aggregate Quantities

We use the policy functions from the household's problem and the distribution of idiosyncratic state variables to construct aggregate quantities for the population of households. The individual state variables are liquid assets  $a$ , the durable stock  $d$ , and idiosyncratic productivity  $z$ . The distribution over these variables is denoted  $\Phi_t(a, d, z)$ . In steady state, the prices are constant,  $r_t = \bar{r}$ ,  $r_t^b = \bar{r}^b$ ,  $Y_t = \bar{Y}$ ,  $p_t = \bar{p}$ , and the steady-state distribution over individual states is stationary and denoted by  $\bar{\Phi}(a, d, z)$ . To compute the steady state of the model, we use the continuous-time methods described in [Achdou, Han, Lasry, Lions, and Moll \(2021\)](#).

Aggregate durable expenditure is the sum of net durable expenditures from adjustments, including the fixed costs of adjustment and maintenance costs

$$X_t = \int \lim_{dt \rightarrow 0} \frac{\text{prob}_{t,t+dt}(a, d, z)}{dt} (d_t^*(a, d, z) - (1 - f)d) d\Phi_t(a, d, z) + \chi \int d d\Phi_t(a, d, z),$$

where  $\text{prob}_{t,t+dt}(a, d, z)$  is the probability that a household with individual state variables  $(a, d, z)$  will make an adjustment between  $t$  and  $t + dt$  and  $d_t^*(a, d, z)$  is the optimal durable stock conditional on adjusting. Since we integrate over changes in durable stocks at the household level,  $X_t$  reflects purchases of durables net of sales of durables. Our definition of  $X_t$  is therefore consistent with the construction of durable expenditure in the national accounts, in which transactions of used durables across households are netted out.

## 2.3. Calibration of the Household Problem

The top panel of [Table I](#) shows the calibrated parameters of the household's problem. We set

$$u(c, s) = \frac{\left[ (1 - \psi)^{\frac{1}{\xi}} c^{\frac{\xi-1}{\xi}} + \psi^{\frac{1}{\xi}} s^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi(1-\sigma)}{\xi-1}} - 1}{1 - \sigma},$$



TABLE I  
CALIBRATION OF THE MODEL.

Parameter	Description	Value	Source
<i>Parameters of the Household's Problem</i>			
$\rho$	Discount factor	0.096	Net Assets/GDP = 0.87
$\sigma$	Inverse EIS	4	See Section 3
$\psi$	Durable exponent	0.581	d/c ratio = 2.64
$\xi$	Elas. of substitution	0.5	See Section 2.3
$\bar{r}$	Real interest rate	0.015	Annual real Fed. Funds Rate
$\bar{r}^b$	Borrowing spread	0.017	Mortgage-Treas. spread
$\delta$	Depreciation rate	0.068	BEA Fixed Asset
$f$	Fixed cost	0.194	Ann. adjustment prob = 0.19
$\theta$	Intensity of match-quality shocks	0.158	See Section 2.4
$\chi$	Required maintenance share	0.35	See Section 2.3
$\nu$	Operating cost	0.048	See Section 2.3
$\rho_z$	Income persistence	0.090	Floden and Lindé (2001)
$\sigma_z$	Income st. dev.	0.216	Floden and Lindé (2001)
$\lambda$	Borrowing limit	0.8	20% Down payment
$\Xi$	Rate of information updating	0.667	Coibion and Gorodnichenko (2012)
<i>General Equilibrium Parameters</i>			
$G/Y$	Steady state govt share	0.2	Convention
$\zeta$	Inverse durable supply elasticity	0.049	See Section 4.3
$\kappa$	Phillips curve slope	0.48	See Section 4.3
$\rho_r$	Real rate persistence	0.60	Estimated over 1991–2007
$\rho_\eta$	Real rate shock persistence	1.55	Estimated over 1991–2007
$\phi_\pi$	Real rate response to inflation	0.79	Estimated over 1991–2007
$\phi_y$	Real rate response to output gap	0.75	Estimated over 1991–2007
$\rho_G$	Nonhousehold demand persistence	0.90	See Section 4.3
$\rho_g$	Productivity growth persistence	0.77	See Section 4.3
$\rho_{r^b}$	Borrowing spread persistence	0.63	Estimated over 1991–2007

where  $\xi$  is the elasticity of substitution between durables and nondurables. Estimates of this elasticity range from substantially below 1 to around 1 (Ogaki and Reinhart (1998), Davis and Ortalo-Magné (2011), Pakoš (2011), Albouy, Ehrlich, and Liu (2016)). We choose an elasticity of  $\xi = 0.5$ , which is at the lower end of these estimates. Choosing a lower value is conservative for intertemporal shifting in that the benefits of accelerating a durable adjustment are smaller.

We set  $\sigma = 4$  implying an EIS of 1/4. This is at the lower end of the range typical in the literature. A low EIS allows the model to match the small response of nondurable consumption to monetary policy shocks we measure in the data (see Section 3). The importance of durables,  $\psi$ , is set to match the average ratio of the nominal values of the total durable stock (durable goods and private residential structures) and annual nondurable consumption (nondurable goods and services excluding housing) from 1970 to 2019.

Our calibration captures a broad notion of durables, which includes residential housing, autos, and appliances among other goods, as in Berger and Vavra (2015). While these goods differ in important respects, such as their depreciation rate and the probability of adjustment, they are all long-lasting and illiquid and purchases are lumpy and infrequent, features we stress in our analysis. Following this broad notion, our depreciation rate  $\delta$  is the annual durable depreciation divided by the total durable stock in the BEA Fixed Asset tables, again averaged from 1970 to 2019. While 73% of the value of the total durable stock consists of residential housing, this component accounts for 23% of the total depre-

ciation owing to the low depreciation rate of structures relative to cars and appliances. This explains why nonhousing durables account for the majority (64%) of spending on durables and are thus important in the determination of aggregate demand.

We set the fixed cost,  $f$ , to target a weighted average of the annual adjustment probabilities of individual durable goods. The three components of the average are the probability that a household moves to a new dwelling (15% per year as reported by [Bachmann and Cooper \(2014\)](#)), makes a significant addition or repair to their current dwelling (2.5% in the PSID), or acquires a new or used car (29.6% in the CEX). We attach a weight of 0.9 to the sum of housing moves and additions and repairs, and a weight of 0.1 to cars, based on the relative value of the housing stock and the car stock in the BEA fixed asset tables. This yields an annual adjustment probability of 0.19. Note that we cannot simply sum the probabilities of adjustments across durable goods, since this would overstate the liquidity of the households' total durable position in our model.

Since our objective is to explain the behavior of real interest rates during and after the Great Recession, we use the years 1991–2007 as a benchmark for interest rates; a period when the economy entered a period of low and stable inflation. The average, ex post, real federal funds rate in terms of nondurables over this period is equal to  $\bar{r} = 1.5\%$ . The steady state borrowing spread  $r^b$  is set to 1.7% based on the difference between the 30-year mortgage rate and the 10-year treasury rate over the same period.

Based on the estimates of [Floden and Lindé \(2001\)](#), we set  $\rho_z = -\log(0.9136)$  and  $\sigma_z = 0.2158$ . We set the discount rate  $\rho$  to match the average liquid financial asset holdings net of mortgage and auto loans to annual GDP ratio over 1970–2019 of 0.87.<sup>3</sup> The borrowing limit is set to  $\lambda = 0.8$  in line with a 20% down payment requirement.

To calibrate the level of maintenance costs, we use NIPA data on housing and car maintenance expenditures. Total maintenance costs are the sum of intermediate goods and services consumed in the housing output table, the PCE on household maintenance, and the PCE on motor vehicle maintenance and repair. We divide these costs by total durable depreciation to arrive at  $\chi = 0.35$ .

Turning to operating costs, taxes on the housing sector, PCE on household utilities, and PCE on fuel oil and other fuels (excluding motor vehicle fuels) amount to 4.1% of the value of the housing stock. For cars, we find that PCE on motor vehicle fuels, lubricants, and fluids amounts to 22% of the value of the stock of vehicles. We sum the operating costs for cars and housing and divide by the total durable stock to obtain  $\nu = 0.048$ .

We set the intensity with which agents update their information set to an annual rate of  $\Xi = 2/3$ , so that the expected time between updates is 6 quarters. An expected information rigidity of 6 quarters is in the middle of the range implied by the estimates of [Coibion and Gorodnichenko \(2012, Table 3\)](#) who find quarterly updating frequencies between 0.11 and 0.24 among professional forecasters, households, and firms.

#### 2.4. *Estimating the Arrival Rate of Match-Quality Shocks*

The intensity of the match-quality shock,  $\theta$ , does not have a natural data counterpart that lends itself to calibration. We estimate this parameter using PSID data and the structural estimation method developed by [Berger and Vavra \(2015\)](#) modified to allow for match-quality shocks. We only provide a brief overview here, with details relegated to Appendix B in the Online Supplementary Material ([McKay and Wieland \(2021\)](#)).

<sup>3</sup>Liquid assets are defined as in [McKay, Nakamura, and Steinsson \(2016\)](#) and [Guerrieri and Lorenzoni \(2017\)](#).



The estimation method centers on matching the probability of a durable adjustment as a function of the “durable gap”  $\omega_{it} \equiv d_{it}^* - d_{it}$ , as well as the density of durable gaps, where  $d_{it}^*$  is the optimal durable stock based on the current state variables. Intuitively, in a fixed-cost model the probability of adjustment should be greater the larger is the absolute gap, since the benefit of adjusting the durable stock is larger.

Gaps are easily computed in the model, since both the optimal durable choice  $d_{it}^{*model}$  and the current durable stock  $d_{it}^{model}$  are known. In the data, we only observe current durable holdings  $d_{it}^{data}$  directly. We infer data gaps using a set of observables  $\mathbf{Z}_{it}^{data}$ , and the model-implied relationship between them and the optimal durable stock,  $d_{it}^{*data} = F^{model}(\mathbf{Z}_{it}^{data})$ , where  $F^{model}$  is the model’s mapping from the observables to  $d^*$ .

The arrival rate of the match-quality shock,  $\theta$ , is primarily identified by the hazard of adjustment for small gaps. Intuitively, at small gaps the household should be relatively far from an adjustment threshold due to the fixed cost, whereas adjustments at large gaps likely reflect that the household crossed an adjustment threshold. Most of the adjustments at small gaps are therefore attributed to the match-quality shock.

Figure 1 plots the model- and data-implied hazards of adjustment conditional on the durable gap at the optimal parameter estimate,  $\theta = 0.1575$ .<sup>4</sup> The bootstrapped 95% confidence band is  $[0.157, 0.159]$ , based on sampling households from the PSID with replacement. The model accounts well for the upward-sloping hazard and explains 80% of the variation in the hazard rate. The adjustment probability for small gaps is substantial in both the model and the data, suggesting that the match-quality shock is quantitatively important.<sup>5</sup> Our estimate implies that 75% of adjustments in steady state are due to the match-quality process.

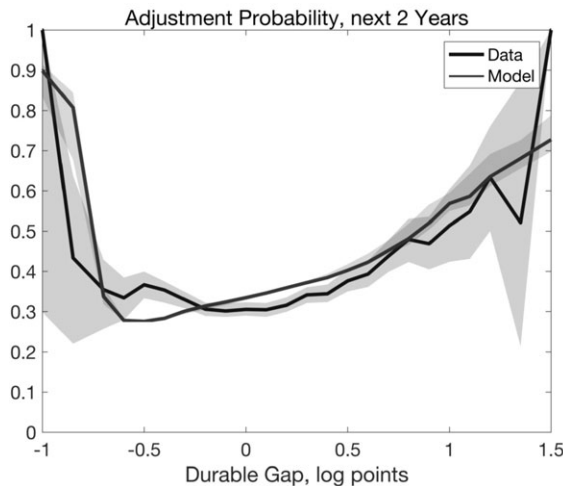


FIGURE 1.—Hazard of adjustment conditional on the durable gap  $\omega = d^* - d$ , where  $d^*$  is the optimal durable choice conditional on adjusting and  $d$  the initial durable stock. Shaded areas are 95% confidence bands.

<sup>4</sup>Appendix Figure A.1 in the Online Supplementary Material plots the density of durable gaps.

<sup>5</sup>We estimate larger adjustment probabilities at small gaps than Berger and Vavra (2015) do because we follow a different approach to identifying adjustments in the data. Berger and Vavra excluded durable adjustments smaller than 20% of the value of the durable stock in part to filter out idiosyncratic moves across location.

### 3. RESPONSE OF DURABLE DEMAND TO MONETARY POLICY

In many fixed-cost models, the timing of durable adjustments is very sensitive to intertemporal incentives (see [House \(2014\)](#)), which poses a challenge in modeling the monetary transmission mechanism because durable demand is excessively responsive to monetary policy (see [Reiter, Sveen, and Weinke \(2013\)](#)). In this section, we show that our model predicts a response of durable demand to interest rates that is in line with several empirical benchmarks. The model is consistent with the magnitude of the spending response as well as the subsequent reversal of this spending that is the hallmark of intertemporal shifting effects. We identify changes in real interest rates in two ways. We begin with identified monetary policy shocks before turning to quasi-experimental evidence.

#### 3.1. Evidence From Identified Monetary Shocks

We use monetary shocks from [Romer and Romer \(2004\)](#), extended by [Wieland and Yang \(2016\)](#), for 1969Q1–2006Q4, as a source of exogenous variation in real interest rates. We estimate the impulse responses of several outcome variables to these shocks. The impulse response functions we estimate are informative about the plausibility of intertemporal shifting effects in the monetary transmission mechanism and also serve as empirical benchmarks for the model.

Our outcome variables are log real GDP per capita; the log of total real durable expenditure per capita,  $x_t = \ln(X_t)$ ; and the extensive margin of durable purchases. To measure the extensive margin, we construct time series for the fraction of the population moving residence each year and the fraction of the population buying a car each quarter using microdata from the PSID and the CEX, respectively.<sup>6</sup>

We estimate the impulse responses using local projections,

$$z_{t+h} = \alpha_h + \sum_{m=0}^M \beta_{h,m} \epsilon_{t-m} + \sum_{l=1}^L \gamma_{h,l} z_{t-l} + \delta_h t + \eta_{t,h}, \quad h = 0, \dots, H,$$

where  $z_t$  is the outcome variable,  $\epsilon_t$  is the Romer–Romer monetary shock, and  $t$  is a time trend.<sup>7</sup> The impulse response function is the sequence  $\{\beta_{h,0}\}_{h=0}^H$ . Standard errors are Newey–West. In our baseline specification, we chose the lag length  $M = L = 16$  quarters. We normalize the Romer shock to yield a 25 basis point decline in the real interest rate on impact. The decline in the real interest rate persists for 3–4 years (see the Appendix, Figure A.3).

The top-left panel of Figure 2 plots our estimated impulse response function for log GDP. It displays a hump-shaped increase that peaks at 0.30% after 9 quarters. For the next 9 quarters, GDP declines and it undershoots its trend before a gradual return to steady state. Both the initial positive peak and the subsequent negative trough are statistically significant at conventional levels. Our estimates suggest that while monetary policy is able to stimulate economic activity in the short run, it comes at the cost of weaker activity in the

<sup>6</sup>Appendix C details the construction of the variables used in this analysis. We construct the annual time series for the probability of moving to a different residence using PSID data from 1969–1997 following [Bachmann and Cooper \(2014\)](#). [Bachmann and Cooper \(2014\)](#) showed that the moving probability from the PSID is in line with the shorter time series from the CPS March Supplement and the AHS. For the probability of buying a car, we use CEX data from 1980–2006.

<sup>7</sup>For the adjustment probabilities, we also include a squared time trend as these time series display a distinct U-shaped pattern.

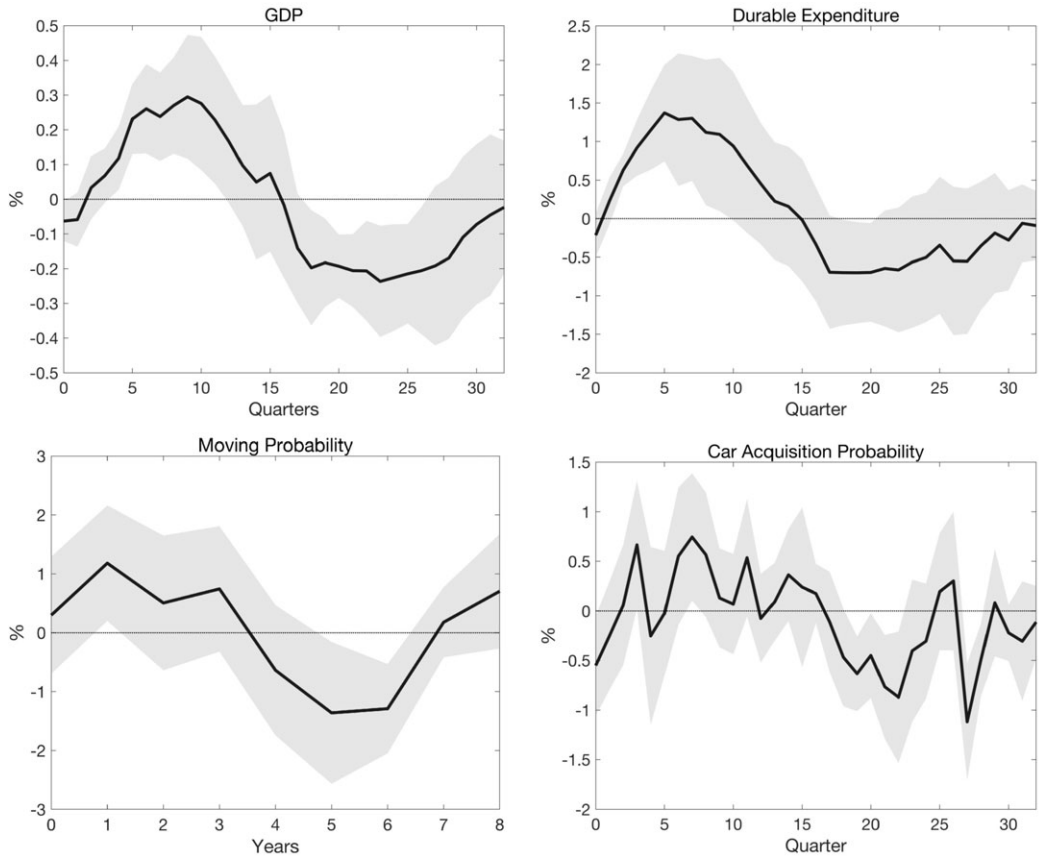


FIGURE 2.—Impulse response function of real GDP (top-left panel), real durable expenditure (top-right), probability of moving house (bottom-left), and probability of buying a car (bottom-right) to a Romer and Romer monetary policy shock. Shaded areas are 95% confidence bands.

medium run. This pattern is consistent with monetary policy borrowing demand from the future. Appendix D in the Online Supplementary Material documents that this result is robust to excluding the deterministic trend, including fewer lagged terms, and restricting the sample to the post-Volcker period.

The panels for real durable expenditure, the moving probability, and the car acquisition probability in Figure 2 provide further evidence for such intertemporal shifting. In each case, we observe a statistically significant positive response to expansionary monetary policy for the first three years followed by a statistically significant contraction. The volatility in the impulse response function for car acquisitions stems in part from the greater sampling variability in this series. These results are consistent with the hypothesis that households accelerate durable purchases following an expansionary monetary shock, but these adjustments are subsequently missing.

In Figure 3, we plot estimates for the cumulative impulse response functions of GDP, durable expenditure, and the extensive margin. These correspond to the integral under the impulse response functions in Figure 2, which reveals the extent to which the initial increase in demand is later reversed. The point estimates of the cumulative impulse response functions are consistent with a complete reversal of GDP and the extensive mar-

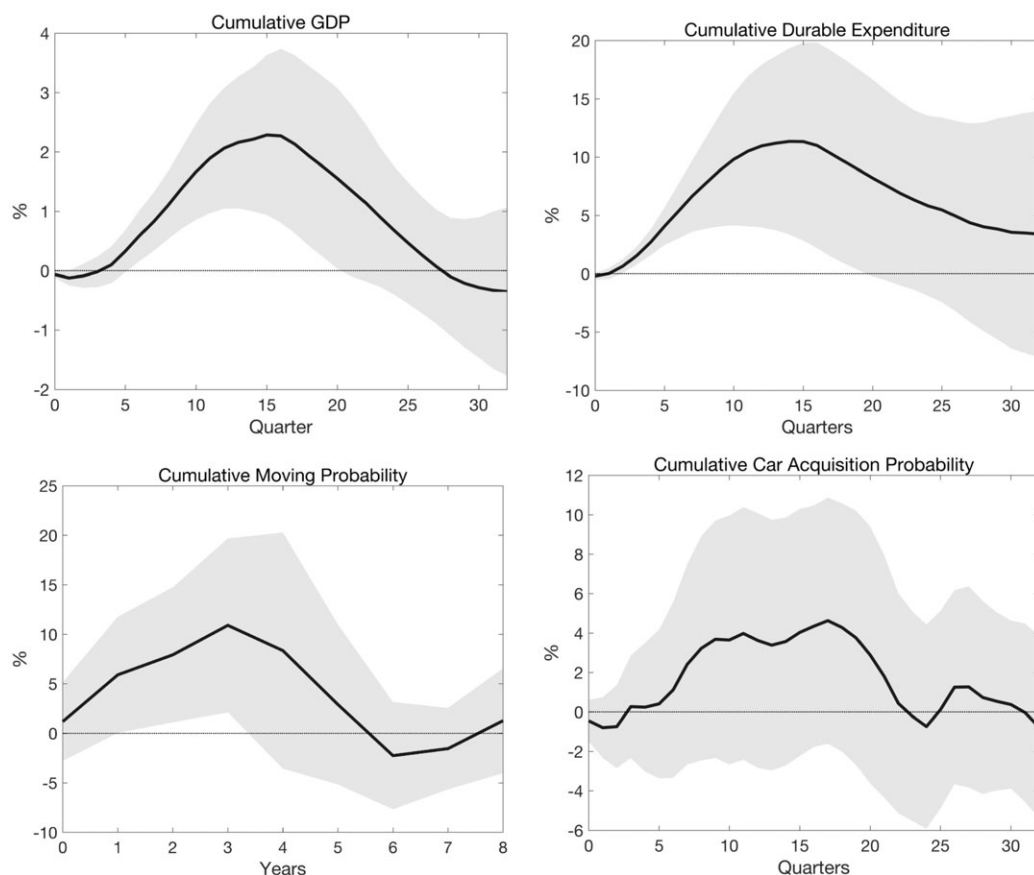


FIGURE 3.—Impulse response function of cumulative real GDP (top-left panel), cumulative real durable expenditure (top-right), cumulative probability of moving house (bottom-left), and cumulative probability of buying a car (bottom-right) to a Romer and Romer monetary policy shock. Shaded areas are 95% confidence bands.

gin, as well as a near-complete reversal of durable expenditure. The near complete reversal of durable expenditure is consistent with long run monetary neutrality, which implies the durable stock will be unaffected in the long run. While the confidence bands on our estimates generally allow for an incomplete reversal, note that from Figure 2 we can reject the hypothesis that no reversal takes place.

We estimate impulse response functions for longer horizons than are typical in the literature, which allows us to observe the intertemporal shifting effects. Typically impulse response functions are reported for up to 16 quarters (see Ramey (2016), for a survey).<sup>8</sup> An exception is Jordà, Singh, and Taylor (2020) who estimate a long-horizon effect of monetary policy using an identification scheme based on “trilemma” shocks. They find GDP is below normal for 12 years following a contractionary shock. Their shock implies that the real interest rate is also elevated for 12 years. In our estimates, the intertempo-

<sup>8</sup>Tenreiro and Thwaites (2016) estimated the response of GDP to Romer and Romer (2004) shocks up to 20 quarters out. Their impulse response functions also display a reversal consistent with what we find.

ral shifting effect of monetary policy only becomes visible once the real rate normalizes, which occurs after 3–4 years for the [Romer and Romer \(2004\)](#) shock.

### 3.2. Evaluating the Model

We now evaluate the model's ability to match the durable spending response to identified monetary policy shocks. Our primary focus is on the magnitude of this response or, in other words, the interest elasticity of durable demand. Limiting this sensitivity poses a challenge and motivates some of the ingredients we include in our model.

To evaluate the model, we estimate the effect of a Romer–Romer shock on the real interest rate,  $r_t$ , aggregate income,  $Y_t$ , and the relative durable price,  $p_t$ , and feed the mean impulse response functions into the household problem of Section 2 starting in steady state.<sup>9</sup> We assume that these paths come as a surprise at  $t = 0$  and then become known to agents when they update their information set. These variables return to steady state after 32 quarters.

The left panel of Figure 4 plots the model-implied cumulative durable expenditures against the data. In our model, the peak real durable response is 11.4%, the same as the peak real durable response in the data. In addition, the model produces a reversal in durable demand within the confidence band.

To highlight that operating and maintenance costs and match-quality shocks are necessary for this success, Figure 4 makes three additional model comparisons.<sup>10</sup> If we omit all of these model elements (see the line labeled “w/o MQ and operating/maint. costs”),

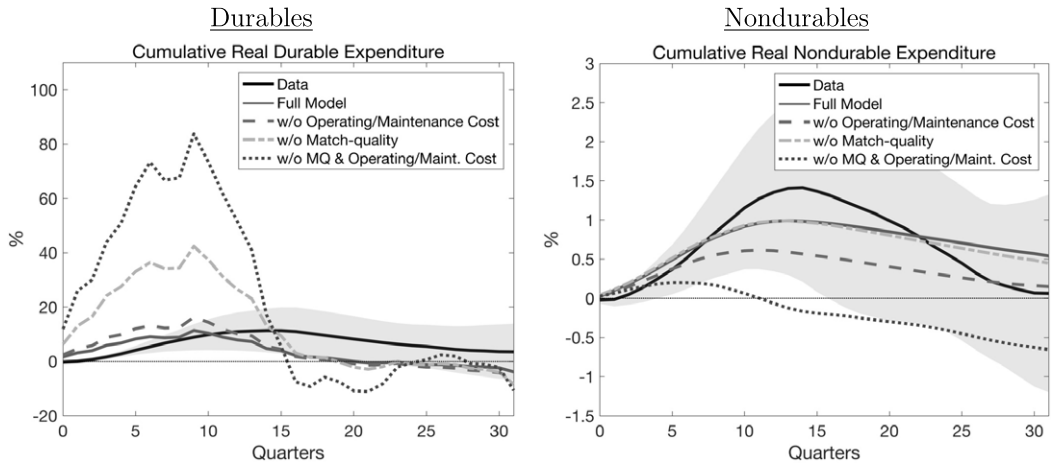


FIGURE 4.—Cumulative response of durable (left) and nondurable (right) expenditure to a simulated monetary policy shock. Model simulations feeding in the estimated impulse responses for  $(Y_t, r_t, p_t)$ . Each panel shows the full model as well as the models that omit one or both of match-quality shocks and operating and maintenance costs.

<sup>9</sup>See Appendix E in the Online Supplementary Material for details and estimates of the impulse response functions for  $r_t$  and  $p_t$ . For log GDP, we use the impulse response function plotted in the top-left panel of Figure 2.

<sup>10</sup>For all of these alternative models, we re-calibrate the discount rate  $\rho$ , the fixed cost  $f$ , and the durable preference  $\psi$  to match our empirical targets for the net liquid asset/GDP ratio, the frequency of adjustment, and the durable-stock-to-nondurable-consumption ratio.

the model predicts that cumulative durable demand peaks at 84%, seven times more than the peak response in the data. The figure also shows the results from omitting either just match-quality shocks or just operating and maintenance costs. The figure shows that it is best to think of these ingredients in multiplicative terms: the match-quality shocks cut the peak cumulative durable response by roughly a factor of four and the operating and maintenance costs cut the peak cumulative durable response by roughly a factor of two.

While the magnitude of the durable expansion in the full model is consistent with the data, it does occur earlier than in the data. The main determinant of how gradually cumulative durable expenditure increases is the information rigidity. Without information frictions, durable expenditure in the first quarter is already as large as the peak cumulative response in our benchmark model. While a larger degree of information rigidity would allow us to get closer to the data on this dimension, it does pull us outside the range of values estimated in the literature. Ultimately, our main results concern a long-horizon forecast for which the degree of information rigidity does not have major quantitative implications so matching the exact timing of durable expenditure in the data is not critical for our purposes.

In the right panel of Figure 4, we show that the full model also provides a good match to the dynamics of cumulative nondurable expenditures. The model without match-quality shocks performs about as well, whereas the model abstracting from both match-quality shocks and operating/maintenance costs predicts too much substitution from nondurable to durable spending. The relatively small nondurable spending response in the data motivated our choice of a relatively low elasticity of intertemporal substitution in Section 2.

Why do operating costs and match-quality shocks reduce the sensitivity of durable demand to interest rate changes? These ingredients play a key role in limiting the sensitivity of the extensive margin of durable demand to intertemporal prices. Match-quality shocks are a source of inframarginal adjustments. We target a certain probability of adjustment in total and by associating more of these adjustments with the match-quality shock, fewer are attributed to households that have hit an  $(S, s)$  band. Therefore, including match-quality shocks, means there are fewer households near the adjustment thresholds that can be induced to accelerate their adjustments by monetary policy.<sup>11</sup> Similarly, operating costs stabilize the extensive margin of demand because they are a component of the user cost of durables that is not sensitive to interest rates. Including operating costs therefore stabilizes the user cost and, therefore, durable demand.

We now show that the willingness of households to shift the timing of their durable adjustments also aligns well with the observed extensive margin responses for cars and housing. For this analysis, we consider two different calibrations that interpret durables more narrowly as either cars or housing, respectively. The primary difference in the calibrations is the depreciation rate. Housing structures depreciate at a much slower rate, 2% per year, while cars depreciate at a much higher rate, 20% per year, than the value-weighted durable stock.<sup>12</sup> As above, we simulate the impulse response for the extensive

<sup>11</sup>The logic of how match-quality shocks affect the extensive margin response of durable demand has antecedents in the literature on price setting (see Golosov and Lucas (2007), Midrigan (2011), Nakamura and Steinsson (2010), Alvarez, Le Bihan, and Lippi (2016)).

<sup>12</sup>The probability of adjustment is also higher for cars (7.4% quarterly) than for housing (15% annually), and households own more housing wealth ( $d/c = 1.92$ ) than car wealth ( $d/c = 0.201$ ). We recalibrate the discount rate  $\rho$ , the fixed cost  $f$ , and the durable exponent  $\psi$  to match these targets, as well as a net-liquid-asset-to-GDP ratio of 0.92 for housing and 1.31 for cars. When we include match-quality shocks, 75% of all adjustments will come from the match-quality process, which is the same fraction as in our estimated model for all durables. This requires  $\theta = 0.12$  for housing and  $\theta = 0.22$  for cars. We only subtract the collateralized



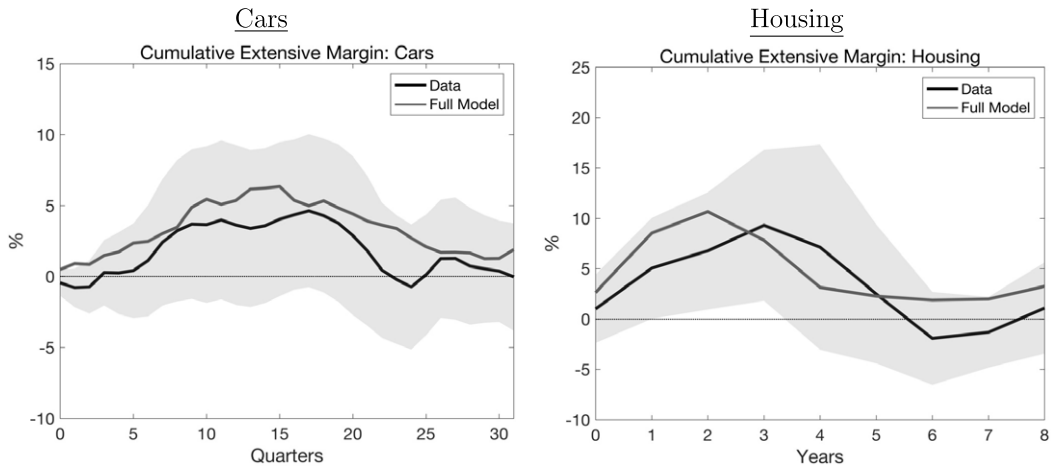


FIGURE 5.—Cumulative response of the extensive margin of durable adjustment to a simulated monetary policy shock. Model simulations feeding in estimated impulse responses for  $(Y_t, r_t, p_t)$ . The panels show the model for cars (left) and the model for housing (right) and the empirical estimates from Section 3.1.

margin by feeding the empirical impulse responses of  $Y_t$ ,  $r_t$ , and  $p_t$  into the model. The left panel of Figure 5 shows that the extensive margin for car adjustments in our model accords well with the data. In both model and data, the extensive margin response is initially positive but then fully reverses. The peak cumulative response is only slightly higher than in the data. The right panel shows the results for the housing model. Our model again accords well with the data. It matches the peak cumulative response and it predicts a reversal very similar to what is observed in the data.

### 3.3. Quasi-Experimental Evidence

We now evaluate the model's ability to fit evidence from quasi-experimental variation in real interest rates. An advantage of this analysis is that it focuses on a narrower set of economic mechanisms than does the preceding analysis of monetary policy shocks because in this case only real interest rates are affected.

There is extensive quasi-experimental evidence that variation in intertemporal prices can shift durable expenditure through time. Empirical studies of anticipated VAT or sales tax changes consistently estimate increases in household durable expenditures followed by complete or near-complete reversals (Cashin and Unayama (2011), D'Acunto, Hoang, and Weber (2016), Baker et al. (2019)). Intuitively, one can interpret the anticipated price increase from a VAT or sales tax increase as a low real interest rate, which is why such policies are termed “unconventional fiscal policy” (Correia et al. (2013)). That low real interest rates pull forward durable expenditures lends credence to our emphasis on intertemporal shifting effects in the monetary policy transmission mechanism.

We now show that our model is quantitatively consistent with the estimates in Baker et al. (2019), who analyze the response of auto sales to anticipated changes in state sales

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loans from liquid assets for the durable we calibrate to. We also allow for a higher borrowing spread  $r^b = 0.03$  in the car model based on the average spread of 4-year car loans with 5-year treasury bonds. For Figure 5, we feed in the estimated impulse response of the relative price of cars in the car model and the estimated impulse response of relative price of housing in the housing model.

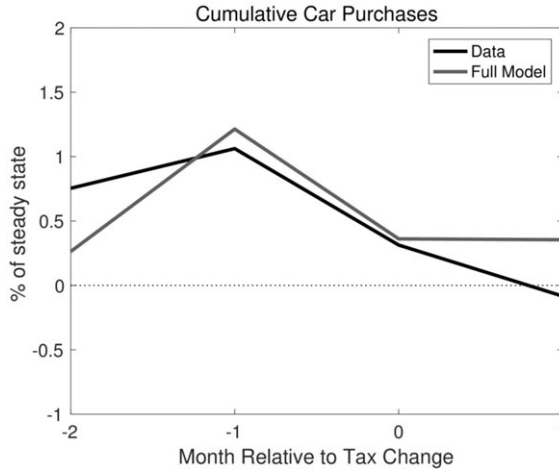


FIGURE 6.—Cumulative car acquisitions for an anticipated sales tax increase in Baker et al. (2019) versus the model. We convert the tax elasticity in Baker et al. (2019) to an interest rate elasticity by dividing by 12.

tax rates.<sup>13</sup> Baker et al. estimated a cumulative 12.7% increase in monthly auto sales leading up to a 1-percentage point increase in sales tax. Such a sales tax change implies an annualized 12% decrease in the real interest rate for cars in the month before the tax increase so the elasticity of the extensive margin of auto sales to interest rates is about  $12.7/12 = 1.1$ .

Using the model calibration that interprets durables as cars, we calculate the response of the extensive margin to a one month drop in the real interest rate with a magnitude of 1% annualized. We assume that the real rate drop is known 5 months ahead of implementation. Baker et al. (2019) reported that sales tax increases are known 2–3 months in advance for referenda and 6–9 months in advance for legislated changes and our assumption is the mid-point of these horizons. As shown in Figure 6, our model produces a peak elasticity of 1.2 and a subsequent reversal that tracks the estimate from Baker et al. quite closely.

#### 4. GENERAL EQUILIBRIUM MODEL

So far we have focused on the household problem, which serves as the demand side of our model. We now specify the supply side and market clearing conditions.

##### 4.1. Production, Labor Supply, and Aggregate Supply

In designing the supply-side of our model, we have a number of objectives. First, one theory of the decline in nondurable consumption and durable expenditure in the Great Recession is that households revised down their expectations for income growth (see De Nardi, French, and Benson (2011), Dupor, Li, Mehkari, and Tsai (2018)). A reduction in income leads households to reduce their consumption expenditure through standard consumption-smoothing logic, but also to reduce their target durable stocks, which leads to an abrupt decline in durable expenditure. To incorporate these effects, we allow for

<sup>13</sup>See their Table 3, Column 1.

shocks to aggregate productivity, which affect income expectations. A second objective in designing the model is to avoid abrupt changes in potential output. Our main results offer a positive explanation of how monetary policy was conducted during and after the Great Recession. In practice, policy makers typically view potential output as evolving in a smooth manner. In keeping with that view, we have designed the model so changes in productivity are serially correlated so that there can be a large change in expectations for permanent income without an abrupt change in realized productivity. For the same reason we also eliminate short-run wealth effects on labor supply, which we do in a manner inspired by [Jaimovich and Rebelo \(2009\)](#).<sup>14</sup> Third, we introduce labor supply into the model in a way that does not alter the household decision problem studied in Sections 2 and 3. This means the model validation performed in Section 3 remains applicable to the general equilibrium model. Achieving this requires an additively separable variant of the [Jaimovich and Rebelo](#) preferences. Fourth, we introduce nominal frictions in the model to generate a conventional New Keynesian Phillips curve. Our objective here is that the Phillips curve should be standard to make clear that our results are driven by the demand side of the model. For this purpose, we adapt the standard sticky-wage environment developed by [Erceg, Henderson, and Levin \(2000\)](#) to allow for uninsured idiosyncratic labor productivity and productivity growth.

We now turn to the specifics of our assumptions. Final goods are produced with a technology that is linear in labor,  $Y_t = Z_t L_t$ , where  $Z_t$  is the exogenous level of productivity and  $L_t$  is aggregate labor supply. Productivity follows the process  $d \ln Z_t = g_t$  where  $g_t$  follows the Ornstein–Uhlenbeck process  $dg_t = -\rho_Z g_t dt + \sigma_Z d\mathcal{W}_t^Z$ , where  $\mathcal{W}_t^Z$  is a standard Brownian motion. Changes to productivity are permanent and the innovations are serially correlated. An innovation to this process can be interpreted as a shock to income expectations that takes some time to fully materialize.

Each household  $i$  supplies a continuum of differentiated labor of type  $j \in [0, 1]$ , with hours denoted  $n_{ijt}$ . We extend the household preferences with an additively separable disutility of labor supply

$$E_0 \int_{t=0}^{\infty} e^{-\rho t} \left[ u(c_{it}, s_{it}) - \Omega_t \int_0^1 v(n_{ijt}) dj \right] dt,$$

$$\Omega_t \equiv \int_0^1 u_c(c_{it}, s_{it}) z_{i,t} Z_t di,$$

where  $\Omega_t$  is a time-varying preference shifter in the spirit of [Jaimovich and Rebelo \(2009\)](#). While Jaimovich–Rebelo preferences limit short-run wealth effects through a [Greenwood, Hercowitz, and Huffman \(1988\)](#) formulation, our desire for additive separability leads us to a different approach, which is to incorporate the productivity-weighted average marginal utility of consumption into  $\Omega_t$ . Jaimovich–Rebelo preferences are compatible with a balanced growth path because the disutility of labor eventually scales with consumption, which is proportional to productivity on the balanced growth path, implying the disutility of labor supply keeps pace with the return to work. We achieve a similar outcome by scaling  $\Omega_t$  by  $Z_t$  directly.

<sup>14</sup>[Cesarini, Lindqvist, Notowidigdo, and Östling \(2017\)](#) provided evidence for small short-run wealth effect on labor supply based on lottery earning in Sweden. [Gali, Smets, and Wouters \(2012\)](#) estimated weak short-run wealth effects on labor supply in aggregate data.

Labor supply is determined by a set of unions as described below and the household takes labor supply and labor income as given. As the disutility of labor is additively separable and labor income is outside the household's control, the decision problem we analyzed in the previous sections is unchanged.

Aggregate labor supply is given by

$$L_t = \left( \int_0^1 l_{jt}^{\frac{\varphi-1}{\varphi}} dj \right)^{\frac{\varphi}{\varphi-1}},$$

where

$$l_{jt} = \int_0^1 z_{it} n_{ijt} di.$$

We now interpret  $z_{it}$  as idiosyncratic labor productivity. In this formulation, each household faces uninsurable risk to their productivity  $z_{it}$ , but face the same (relative) exposure to each variety of labor  $j$ .

The final good is produced by a representative firm. Prices are flexible and equal to nominal marginal cost:  $P_t = W_t/Z_t$ , where  $W_t$  is the price index associated with the aggregator  $L_t$ . The real wage is then  $W_t/P_t = Z_t$ .

We obtain a standard New Keynesian Phillips curve through sticky nominal wages. A continuum of unions set the nominal piece rate,  $\tilde{W}_{jt} = W_{jt}/Z_t$ , of each type of labor. Specifying wages as a piece rate implies that nominal prices inherit the stickiness of wages, without us needing to incorporate additional pricing frictions. The union maximizes the equally-weighted utility of the households subject to a Rotemberg-style adjustment cost of  $\frac{\Psi}{2} \Omega_t L_t (\mu_{jt})^2$ , where  $\Psi$  is a parameter that controls the strength of the nominal rigidity and  $\mu_{jt}$  is the growth rate of  $\tilde{W}_{jt}$  such that  $d \ln \tilde{W}_{jt} = \mu_{jt} dt$ .<sup>15</sup> Among union workers supplying type  $j$ , all labor is equally rationed,  $n_{ijt} = l_{jt}$ . In a symmetric equilibrium, all workers supply  $L_t$  units of labor and each household receives real, pre-tax income of  $z_{it} Y_t$ . Appendix F in the Online Supplementary Material presents the union's problem in detail and shows that the linearized symmetric equilibrium gives rise to the following Phillips curve

$$\dot{\pi}_t = \rho \pi_t - \kappa \left( \frac{Y_t - \bar{Y}_t}{\bar{Y}_t} \right), \quad (1)$$

where  $\pi_t = \frac{d \ln P_t}{dt}$  and  $\bar{Y}_t$  is potential output. This is a continuous-time version of the standard New Keynesian Phillips curve.

We now turn to the supply of durable goods. The durable good is produced by a representative firm using the production function,

$$X_t = v Z_t^\zeta M_t^{1-\zeta} \bar{H}^\zeta,$$

where  $X_t$  is the production of durables,  $M_t$  is the input of the nondurable good, and  $v$  is a constant. The constant flow  $\bar{H}$  of land is made available and sold by the government

<sup>15</sup>We model the Rotemberg adjustment cost as a utility cost for the union rather than as a resource cost based on the arguments in Eggertsson and Singh (2019).

at a competitive price.  $Z_t$  enters the production function here in a manner that is “land-augmenting” so that the long-run relative price of durables is unaffected by permanent TFP shocks. The first-order conditions of this problem lead to a relative price of

$$p_t = (1 - \zeta)^{-1} v^{-\frac{1}{1-\zeta}} \left( \frac{X_t}{Z_t \bar{H}} \right)^{\frac{\zeta}{1-\zeta}}. \quad (2)$$

Thus,  $(1 - \zeta)/\zeta$  is the supply elasticity of the durable good.

The final good is used for several purposes including nondurable consumption, an input into durable production, and government consumption. In addition, we interpret the spread between the borrowing and saving interest rates as reflecting an intermediation cost. We assume the intermediation cost follows an Ornstein–Uhlenbeck process given by  $dr_t^b = -\rho_{r^b}(r_t^b - \bar{r}^b)dt + \sigma_{r^b}d\mathcal{W}_t^{r^b}$ . Appendix F in the Online Supplementary Material shows the market-clearing conditions of the model.

#### 4.2. Government

Monetary policy is governed by a standard interest rate rule,

$$\dot{r}_t = -\rho_r(r_t - \bar{r}) + \phi_\pi \pi_t + \phi_y \frac{Y_t - \bar{Y}_t}{\bar{Y}_t} + \eta_t^r,$$

where the first term captures interest rate smoothing, the second and third terms capture the endogenous monetary policy response, and  $\eta_t^r$  is an exogenous term that follows  $d\eta_t^r = -\rho_\eta \eta_t^r dt + \sigma_\eta d\mathcal{W}_t^\eta$ .

Fiscal policy consists of a constant debt policy,

$$A_t = \int_0^1 a_{it} dt = \bar{A}. \quad (3)$$

We assume that the government levies taxes proportional to  $z_{it}$  where the tax rate  $\bar{\tau}_t$  is set to satisfy the government budget constraint so we have

$$y_{it} = (Y_t - \bar{\tau}_t)z_{it}$$

and the period-by-period government budget constraint is  $\bar{\tau}_t = r_t \bar{A} + G_t$ , where  $G_t$  is an exogenous level of government consumption.<sup>16</sup> We assume that  $G_t$  follows an Ornstein–Uhlenbeck process,  $d \ln G_t = -\rho_G(\ln G_t - \ln \bar{G})dt + \sigma_G d\mathcal{W}_t^G$ . In our analysis, government consumption will stand in for changes in demand that originate outside the household sector and we will at times refer to “nonhousehold demand.”

#### 4.3. Calibration of the General Equilibrium Model

The bottom panel of Table I shows the calibrated parameters associated with the supply side of the economy and the government. We set  $v$  to normalize the relative price of

<sup>16</sup>The government also raises a small amount of revenue from selling land. In steady state, this amounts to 0.5% of GDP. For computational convenience, we assume this revenue finances an independent stream of spending.

durables to one in steady state. We calibrate the inverse supply elasticity of durable goods to  $\frac{\zeta}{1-\zeta} = 0.049$ . Our choice of  $\zeta$  reflects land's share in the production of durables, which we calculate as follows. Residential investment is on average 36% of broad durable consumption expenditures (NIPA Table 1.1.5, 1969–2007). New permanent site structures account for 58% of residential investment (NIPA Table 5.4.5). Davis and Heathcote (2007) reported that 11% of sales of new houses reflect the value of land. Therefore, payments for new land amount to a little over 2% of the expenditure on durables. However, Davis and Heathcote (2007) also reported that the existing stock of housing is paired with more valuable land and land accounts for 36% of the value of the housing stock, which is substantially larger than the 11% share in new housing. In our model, durables trade at a single price so there is no distinction between the cost of creating new durables and the value of the stock. We therefore take the mid-point of 11% and 36%, which implies that payments to land account for 5% of expenditure on durables.

An elastic supply of durable goods is consistent with the small relative price response we estimate in response to monetary shocks (see Figure A.3 in the Online Supplementary Material). An elastic supply of durable goods also finds some support from Goolsbee (1998) and House and Shapiro (2008) who present evidence on the response of capital goods prices to policies that stimulate investment demand. House and Shapiro found little evidence of a price response and argue for a high supply elasticity. Goolsbee argued for less elastic supply in general, but for the categories of goods that also serve as consumer durables (autos, computers, and furniture) he finds little price response.<sup>17</sup>

The slope of the Phillips curve is 0.48. The slope of the Phillips curve is expressed in terms of the change in annualized inflation for a unit of the output gap per year so one needs to divide by 16 to compare to a quarterly discrete-time model, which yields a slope of 0.03. That value is squarely in the middle of empirical estimates (Mavroeidis, Plagborg-Møller, and Stock (2014)).

We estimate the monetary policy rule from 1991–2007, since there is no significant trend in the real rate over this period. This yields  $\rho_r = 0.60$  (equivalent to a quarterly persistence of 0.86),  $\phi_\pi = 0.79$ ,  $\phi_y = 0.75$ , and  $\rho_\eta = 1.55$  (equivalent to a quarterly persistence of 0.68).<sup>18</sup> We also estimate the process for the borrowing spread over 1991–2007, which yields  $\rho_{r,b} = 0.63$  and is equivalent to a quarterly persistence of 0.85. We set the persistence of the nonhousehold demand shock  $\rho_G = 0.42$  equivalent to a quarterly persistence of 0.9. We deliberately choose a value at the lower end of the persistence spectrum typically estimated for demand shocks, since a more persistent shock naturally has more persistent effects on  $r^*$ . This is a conservative choice, since we emphasize the prolonged low levels of  $r^*$  after the Great Recession. Similarly, we set  $\rho_g = 0.77$  equivalent to a quarterly persistence of 0.83 such that an innovation to productivity achieves 90% of its long-run level within 3 years. This speed of convergence strikes a balance between our focus on cyclical developments and a smooth evolution of potential output.

#### 4.4. Solving the Model

We use the sequence-space approach of Auclert et al. (2021) to solve for the aggregate dynamics of the economy. The first step in this method is to compute the partial equi-

<sup>17</sup> An alternative explanation for the muted relative durable price response to monetary policy shocks is nominal rigidities in the durables sector. Both formulations should have similar implications for durable demand provided that they generate similar dynamics for relative prices.

<sup>18</sup> The long-run responses are  $\frac{\phi_\pi}{\rho_r} = 1.26$  and  $\frac{\phi_y}{\rho_r} = 1.31$ . Note that our estimated rule satisfies the conventional Taylor principle since it is specified in terms of a real rate.



librium response of aggregate variables to changes in prices and aggregate shocks under perfect foresight. To do so, we approximate the value functions and policy rules at discrete time steps as is standard practice (see [Achdou et al. \(2021\)](#)). We use quarterly time steps. We then arrive at a set of partial equilibrium Jacobians in which the  $(i, j)$  elements relate changes in aggregate quantities at a horizon of  $i$  quarters to changes in prices or shocks at a horizon of  $j$  quarters. We then translate the partial equilibrium Jacobians of the model into general equilibrium Jacobians by solving for the endogenous prices that satisfy the market clearing conditions (2) and (3). See Appendix A in the Online Supplementary Material for details. This procedure assumes that the economy's dynamics are linear in the aggregate states but allows for nonlinear policy rules with respect to idiosyncratic states. The solution is equivalent to the impulse response functions obtained from a perturbation approach such as the [Reiter \(2009\)](#) method (see [Boppart, Krusell, and Mitman \(2018\)](#)).

During the Great Recession, the economy hit the ELB, which creates a kink in the response of the interest rates with respect to the state of the economy. We will incorporate the ELB with a sequence of monetary news shocks, which captures the effect of the ELB on the expected path of rates.<sup>19</sup> We have also investigated the robustness of our results to nonlinear aggregate dynamics. We return to both of these issues below.

## 5. THE MONETARY TRANSMISSION MECHANISM

The acceleration of durable purchases in response to monetary policy stimulus implies that monetary policy shifts demand intertemporally. This feature of the monetary transmission mechanism is captured by the sequence-space Jacobian of the output gap with respect to real interest rates. We call it the “monetary transmission matrix” and denote it by  $\mathcal{M}$ . The  $(i, j)$  element of  $\mathcal{M}$  gives the general equilibrium response of the output gap at a horizon of  $i - 1$  quarters with respect to news about real interest rates at a horizon  $j - 1$  quarters,

$$\mathcal{M} = \begin{pmatrix} \frac{d\hat{Y}_0}{dr_0} & \frac{d\hat{Y}_0}{dr_1} & \cdots \\ \frac{d\hat{Y}_1}{dr_0} & \frac{d\hat{Y}_1}{dr_1} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix},$$

where  $\hat{Y}_t = \frac{Y_t - \bar{Y}_t}{\bar{Y}_t}$  is the output gap. The discrete-time nature of this matrix reflects the quarterly time steps on which we approximate the solution of the model. The below-diagonal elements of  $\mathcal{M}$  show how the output gap responds to monetary stimulus in the past and, therefore, are informative about intertemporal shifting.

To illustrate how  $\mathcal{M}$  captures the intertemporal shifting of aggregate demand, in the left panel of Figure 7, we plot columns one, five, and nine of our model's  $\mathcal{M}$  multiplied by  $-0.01$ . These show the impulse response function of the output gap to a surprise 1% (annualized) real interest rate cut that occurs in the current quarter (column 1), 4 quarters from now (column 5), and 8 quarters from now (column 9). In each case, output expands in the run-up to the interest rate cut, but once stimulus is removed, output falls below steady state. The initial increase in output primarily reflects the low user cost of durables.

<sup>19</sup>Our method of incorporating the ELB through news shocks is an implementation of the method described by [Holden and Paetz \(2012\)](#).

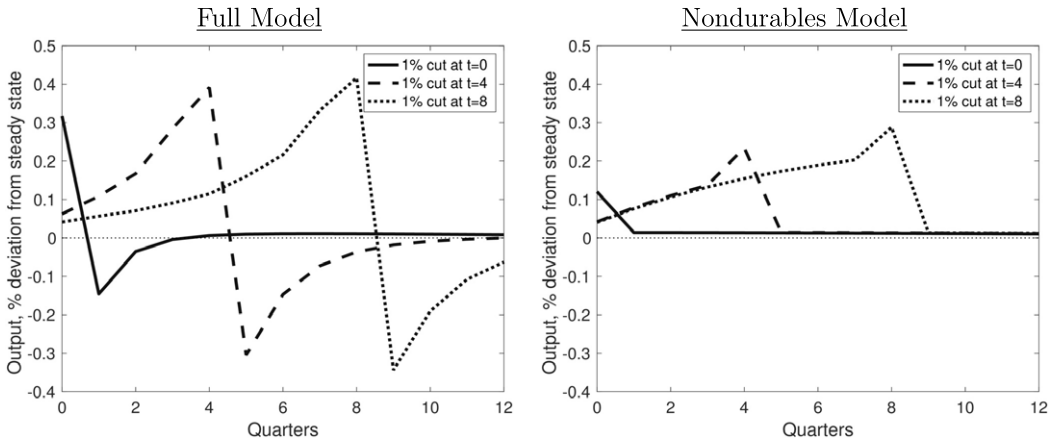


FIGURE 7.—Percentage change in output following a 1% reduction in the real interest rate at horizons  $t = 0$  (solid line),  $t = 4$  (dashed line), and  $t = 8$  (dotted line). The left panel shows the effect in the full model, and the right panel shows the effect in the nondurables model.

While the real interest rate falls only at one date, the user cost falls before that date due the anticipated increases in the relative price of durables. The subsequent decline in output reflects missing durable demand as durable adjustments are shifted earlier in time.

To show that the intertemporal shifting of aggregate demand is a consequence of durable demand, the right panel of Figure 7 plots the same columns in a model with only nondurable goods. The nondurables model contains the same set of ingredients as our full model (e.g., idiosyncratic risk, sticky information) but it abstracts from durable consumption. We calibrate the intertemporal elasticity of substitution,  $\sigma^{-1}$ , to match the peak output effect in our full model in response to a 1% reduction in the real interest rate that lasts for 9 quarters ( $t = 0$  to  $t = 8$ ).<sup>20</sup> In this model, the output responses to interest rate cuts are positive at all horizons so there is no intertemporal shifting. The increasing output effect for more distant interest rate cuts reflects the fact that more households will have learned of the shock. The spike in output when the interest rate cut occurs reflects the redistribution from creditors to debtors (see Auclert (2019)).

Several recent studies explore the role of marginal propensities to consume in amplifying changes in demand that are directly generated by monetary policy (e.g., Kaplan, Moll, and Violante (2018), Auclert, Rognlie, and Straub (2020)). While our model does well in matching the aggregate response of durable expenditure, nondurable consumption, and the extensive margin to monetary policy shocks (see Section 3), its average marginal propensity to spend is below typical empirical estimates registering 0.19 per quarter for total expenditure and 0.04 for nondurable expenditure. The low marginal propensity to spend reflects the fact that households in the model can easily borrow against the value of their durables. We have found that tightening the borrowing limit raises the marginal propensity to spend but has little impact on the intertemporal shifting effects we focus on.

<sup>20</sup>The durable share in utility is set to zero,  $\psi = 0$ , rendering  $\delta$ ,  $\xi$ ,  $f$ ,  $\theta$ ,  $\nu$  irrelevant. The borrowing limit is set to  $-\lambda$  times the 25th percentile of durable holdings in our full model. The parameter  $\rho$  is set to match the same net asset to GDP ratio as in the full model. All other parameters are identical to the full model.

## 6. INTEREST RATES DURING AND AFTER THE GREAT RECESSION

We now turn our attention to the evolution of the real interest rate,  $r$ , and the natural rate of interest,  $r^*$ , during and after the Great Recession. The intertemporal shifting effects in our model imply that interest rate changes are very persistent. The model therefore predicts that the accommodative monetary policy during the Great Recession will be followed by low interest rates for many years.

6.1. *The Great Recession Through the Lens of the Model*

We use a filtering approach to extract the shocks that account for the aggregate time series during the Great Recession. We seek to match four aggregate time series from 1991–2019:<sup>21</sup> the output gap,  $\hat{Y}_t$ , constructed using the CBO's estimate of potential output; the change in the durable expenditure share (relative to potential GDP),  $s_t^x - s_{t-1}^x$  where  $s_t^x = \frac{p_t x_t}{\hat{Y}_t}$ ; the demeaned ex ante real interest rate,  $r_t - \bar{r}$ , based on the Federal Funds Rate net of average nondurable inflation from 1991–2007; and the demeaned spread of the 30-year mortgage rate over the 10-year treasury yield,  $r_t^b - \bar{r}^b$ .<sup>22</sup>

We will extract quarterly aggregates of the innovations to the exogenous processes  $\mathcal{W}_t^Z$ ,  $\mathcal{W}_t^G$ ,  $\mathcal{W}_t^\eta$ , and  $\mathcal{W}_t^b$  from the data. They correspond to the productivity shock, the non-household demand shock,<sup>23</sup> the monetary policy shock, and the shock to the borrowing spread.

We use a novel filtering algorithm that we describe in detail in Appendix G in the Online Supplementary Material. For each of the shocks, we construct the impulse response functions of  $\{\hat{Y}, \Delta s^x, r - \bar{r}, r^b - \bar{r}^b\}$ , which are reported in Appendix I in the Online Supplementary Material. We then proceed recursively: at each date  $t$ , we create a forecast for  $\{\hat{Y}_t, \Delta s_t^x, r_t - \bar{r}, r_t^b - \bar{r}^b\}$  based on all the previous shocks we have filtered. We then solve for the innovations at date  $t$  that explain the difference between the data observed at date  $t$  and our forecast. We make use of the assumption that the economy's dynamics are linear in the shocks to perform this calculation. Specifically, the forecast for the data is a convolution of the previous shocks and the impulse response functions and solving for the date  $t$  shocks requires inverting a matrix of the impact response of each data series with respect to each shock. We initialize this procedure in 1991 assuming the economy is in steady state. The specific initialization date has negligible effects on the shocks we filter during the Great Recession. This filtering method is equivalent to the Kalman filter (and also the Kalman smoother) given that there is no measurement error and the initial state is known with certainty (see Appendix G). The benefit of this approach to filtering is that it relies only on impulse response functions and does not require a state transition matrix, which is not readily available for a heterogeneous agent model in which the state includes a distribution.

<sup>21</sup>We chose 1991 as a starting date for three reasons. First, it is sufficiently distant from the Great Recession that the initial state of the economy should have little effect on the dynamics of the economy during the Great Recession. Second, the real rate displays no trend from 1991 through 2007, which side-steps issues for how to detrend the real rate. Third, the persistence of inflation is small and statistically insignificant after 1991, and this is a key input the determination of nondurable inflation expectations, and thus the ex ante real rate. (The persistence is much higher before 1991.)

<sup>22</sup>We demean the series using the mean from 1991–2007, so as to not incorporate the downward-trend in the real rate during the Great Recession.

<sup>23</sup>In this section, we label the government spending shock “nonhousehold demand shock” since its role is to account for the residual output gap that cannot be explained by the shocks to households.

The ELB was an important constraint on monetary policy during the Great Recession, and we explicitly incorporate it into our filtering procedure. In measuring the ex ante short-term real interest rate, we assume expected inflation is constant. Given this assumption, the ELB on the Federal Funds rate directly translates into an effective lower bound for the ex ante real rate,  $r \geq \underline{r} = -2.5$ .<sup>24</sup> As the measured real interest rate never violates this constraint, our filtering algorithm naturally imposes it through realizations of monetary policy shocks. However, as these shocks are expected to dissipate over time, it is possible for the expected path of rates to violate the constraint. To ensure this does not happen, we incorporate monetary news shocks. At any point in time  $t$  for horizon  $h \geq 1$ , we calculate the extent to which the path violates the ELB,  $\mathbb{E}_t r_{t+h}^{\text{news}} = \max\{\underline{r} - \mathbb{E}_t r_{t+h}, 0\}$ . We then introduce  $\{\mathbb{E}_t r_{t+h}^{\text{news}}\}_{h=1}^H$  as news shocks about the future path of the real interest rate. Because the monetary news shocks affect the variables we target,  $\{\hat{Y}_t, \Delta s_t^x, r_t - \bar{r}, r_t^b - \bar{r}^b\}$ , we must also update our inference on the other shocks. The updated set of shocks and the monetary news shocks imply a new forecasted path for the real rate. We again check whether it violates the ELB. If it does, we keep iterating on this procedure until the ELB constraint is satisfied.

The shocks are uniquely identified as they imply very different impulse response functions for  $\{\hat{Y}, \Delta s^x, r - \bar{r}, r^b - \bar{r}^b\}$ . A permanent decline in productivity causes a durable overhang, with a large reduction in durable spending, a negative output gap, and a reduction in the real rate as the central bank accommodates. A negative nonhousehold demand shock causes a negative output gap along with an increase in durable spending to potential GDP as accommodative monetary policy stimulates durable expenditure. A contractionary monetary policy shock causes a negative output gap and reduces durable spending relative to potential GDP, accompanied by an increase in the real rate. Finally, a shock to the borrowing spread is easily identified as it is the sole source of variation in  $r^b$ . This spread can account for a divergence between interest rates on Treasuries and household debt due to, for instance, convenience yield.

In Figure 8, we plot the filtered shocks scaled by their impact on the contemporaneous output gap. Our procedure identifies large negative productivity shocks during the Great Recession owing to the persistent weakness in durable spending along with low real interest rates. A permanent decline in productivity is akin to an overbuilding shock in the sense that the economy now has more durables than it would like. With some delay our filter also identifies a fall in nonhousehold demand as the productivity shocks are not sufficient to explain the decline in the output gap. While borrowing spread shocks are prevalent in the run-up to the financial crisis they have little effect on the output gap.<sup>25</sup> Monetary policy shocks tend to be slightly positive throughout the Great Recession, as the other shocks predict a decline in real interest rates that is not feasible due to the ELB constraint.

## 6.2. The Slow Normalization of Rates After the Great Recession

Figure 9 shows our main result: Our model predicts a very slow normalization of interest rates after the Great Recession. We plot the model's forecast of the real interest rate

<sup>24</sup>The bound is equal to the ELB on the Federal Funds rate, equal to 0.15%, net of the average nondurable inflation from 1991–2007, which is equal to 2.65%.

<sup>25</sup>The spread between mortgages rates and Treasuries only displayed a short-lived spike. This contrasts with the behavior of convenience yields, as measured by the spread between corporate bonds and US Treasuries, which were particularly elevated in the years following the Great Recession (e.g., Del Negro et al. (2017)). The decline in real interest rates faced by households during and after the Great Recession implies factors beyond convenience yields are needed to explain the low level of policy rates over this period.

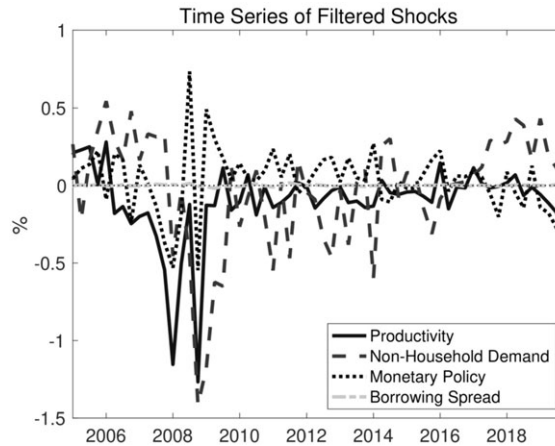


FIGURE 8.—Aggregate shocks filtered from the output gap, the real interest rate, the change in durable spending as a fraction of potential output, and the mortgage-Treasury spread. The shocks are scaled based on their contemporaneous effect on the output gap.

against the data. To construct the figure we use the filtered shocks up to 2012Q4 and then use the model to forecast real interest rates through 2019Q4. The model predicts that the ELB will continue to bind until 2015Q4, when lift-off did in fact occur. Even after lift off, the normalization occurs slowly. The model predicts the real interest rate will remain 2.7 percentage points below steady state in 2017Q4 and 1.8 percentage points below steady state in 2019Q4, which closely tracks the interest rate path that came to be realized. The model fits the real interest rate exactly up to 2012Q4 by construction because it is one of the series we match in our filtering. We use the beginning of 2013 as a benchmark for our forecasts because the taper tantrum of May 2013 reflected the first intentions of the Federal Reserve to begin the tightening cycle. But the model predicts a very persistent ELB episode even early on in the Great Recession.

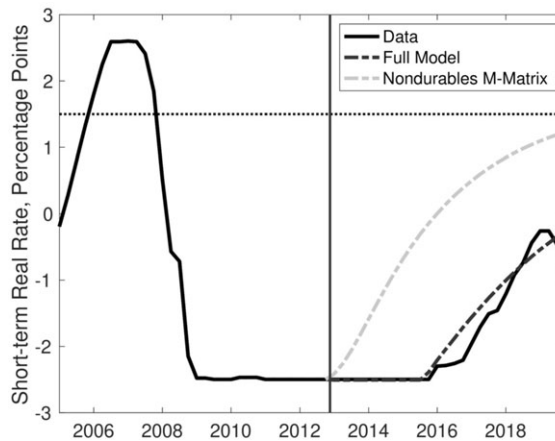


FIGURE 9.—Real interest rate from the model (forecasted after 2012Q4), and ex ante real interest rate in the data. The dotted horizontal line is the steady state real interest rate, equal to 1.5%.

According to our simulation, cyclical factors occurring before 2013 generate the persistently low levels of interest rates during and after the Great Recession and the late lift-off of interest rates in December 2015. This suggests that one does not need to appeal to secular forces, such as demographics, to explain the behavior of real interest rates over this period.

The intertemporal shifting of durable demand in the model is key to the slow normalization of real interest rates following the Great Recession. One way to show this is the following thought experiment: What would have happened if the monetary transmission mechanism in the model worked just as the monetary transmission mechanism in the nondurables model? To implement this experiment, we replace the  $\mathcal{M}$  matrix in the full model with the  $\mathcal{M}$  matrix from the nondurables model described in Section 5. We then filter the data and produce a new forecast for the real interest rate after 2012Q4. Figure 9 shows that the nondurables  $\mathcal{M}$  matrix predicts a much more rapid normalization of real interest rates. This is because under the nondurables  $\mathcal{M}$  matrix, monetary policy does not need to keep interest rates low to counteract intertemporal shifting effects from past monetary stimulus.

### 6.3. Definition of $r^*$ and the Role of Intertemporal Shifting

As we show next, the slow normalization of real interest rates in the model reflects a slow normalization of the natural rate of interest,  $r^*$ . The natural rate normalizes slowly primarily because low interest rates themselves reduce future demand thereby bringing about low interest rates again in subsequent periods and propagating low rates forward in a circular fashion.

We define  $r^*$  as the real interest rate that is consistent with a zero output gap. To implement this definition, we must account for the fact that the current output gap depends not just on the contemporaneous interest rate but also on expectations of future real interest rates. Therefore, at date  $t$  we seek a path for real interest rates going forward that is consistent with a zero output gap at  $t$  and an expectation that the output gap will remain zero going forward.

The sequence space allows for a convenient method to solve for  $r^*$ . Define

$$\vec{\hat{Y}}_t \equiv (\hat{Y}_t, \mathbb{E}_t \hat{Y}_{t+1}, \mathbb{E}_t \hat{Y}_{t+2}, \dots)'$$

as the vector of time  $t$  forecasts of output gaps at all future dates,

$$\vec{r}_t \equiv (r_t - \bar{r}, \mathbb{E}_t r_{t+1} - \bar{r}, \mathbb{E}_t r_{t+2} - \bar{r}, \dots)'$$

as the vector of time  $t$  forecasts of real interest deviations at all future dates, and define  $\eta_t \equiv (g_t, G_t - \bar{G}, r_t^b - \bar{r}^b)'$  as the vector of exogenous stochastic processes. In Appendix H of the Online Supplementary Material, we show using a first-order approximation around steady state that

$$\vec{\hat{Y}}_t = \mathcal{M} \vec{r}_t + \mathcal{Q} \eta_t + \mathcal{D}(\Phi_t - \bar{\Phi}), \quad (4)$$

where  $\Phi_t$  is the distribution of households over idiosyncratic states. In this context,  $\Phi_t$  can be interpreted as a vector that gives a discrete representation of the distribution as in the [Reiter \(2009\)](#) method of solving heterogeneous agent models.  $\mathcal{M}$  is the monetary transmission matrix we introduced in Section 5 in which the  $(i, j)$  element gives the sensitivity



of the output gap at horizon  $i - 1$  to real interest rate changes at horizon  $j - 1$ . The matrix  $\mathcal{Q}$  contains the impulse response functions of shocks to  $\eta$  on the output gap, with the  $k$ th column corresponding to the  $k$ th shock and row  $i$  corresponding to horizon  $i - 1$ . The impulse responses in  $\mathcal{Q}$  are calculated under the assumption of no change in real interest rates. The matrix  $\mathcal{D}$  captures how changes in the distribution of idiosyncratic states affect the output gap.

$\vec{r}_t^*$  is defined as the vector that sets  $\vec{\hat{Y}}_t = 0$ . Using equation (4), we have

$$\vec{r}_t^* = -\mathcal{M}^{-1}(\mathcal{Q}\eta_t + \mathcal{D}(\Phi_t - \bar{\Phi})).$$

$\vec{r}_t^*$  is a function of the state of the economy—as is clear from the equation above—and the past behavior of real interest rates affects  $\vec{r}_t^*$  through the distribution of individual states  $\Phi_t$ .

In Appendix H, we show that we can compute  $r^*$  using the matrices  $\mathcal{M}$  and  $\mathcal{Q}$  as well as the filtered shocks and real rate expectations, assuming that we start in steady state at  $t = 0$ ,

$$\begin{aligned} \vec{r}_t^* = & -\sum_{k=0}^{t-1} \mathcal{M}_{[1+t-k, \dots, 1+t-k]}^{-1} \mathcal{M}_{[1+t-k, \dots, 1+t-k]} \left[ \mathbb{E}_k \begin{pmatrix} r_k \\ \vdots \\ r_{t-1} \end{pmatrix} - \mathbb{E}_{k-1} \begin{pmatrix} r_k \\ \vdots \\ r_{t-1} \end{pmatrix} \right] \\ & - \sum_{k=0}^t \mathcal{M}_{[1+t-k, \dots, 1+t-k]}^{-1} \mathcal{Q}_{[1+t-k, \dots]} [\mathbb{E}_k(\eta_k) - \mathbb{E}_{k-1}(\eta_k)]. \end{aligned} \quad (5)$$

Importantly, we do not need to infer the high-dimensional state from the data to compute  $r^*$ . We do assume that we start in steady state at  $t = 0$ , but the importance of this assumption vanishes over time. In particular, making this assumption in 1991 has negligible consequences for our inference about  $r^*$  during the Great Recession.

To understand the intuition behind equation (5), start with the second term that involves the surprise in the exogenous processes  $\eta_k$  and set  $k = 0$ . The matrix  $\mathcal{Q}_{[1+t, \dots]}$  tells us how a shock at time 0 affects the output gap from time  $t$  onward. The operation  $-\mathcal{M}_{[1+t, \dots, 1+t]}^{-1}$  then determines how interest rates from  $t$  onward must move to close this output gap. We repeat this idea for all shocks that have occurred from date 0 to date  $t$  and sum the implied interest rate movements. This is the contribution of the fundamental shocks to  $r^*$  at date  $t$ .

The first term in equation (5) is the contribution of intertemporal shifting. It captures how past interest rate movements affect  $r^*$  going forward. To understand the intuition, again start with  $k = 0$ . The term in square brackets tells us the news about the real rate path up to  $t - 1$  that arrived at date 0.<sup>26</sup> The  $\mathcal{M}_{[1+t, \dots, 1+t]}$  matrix multiplying this term converts these news into changes in the output gap for time  $t$  onward. And the  $-\mathcal{M}_{[1+t, \dots, 1+t]}^{-1}$  operation then determines how interest rates from  $t$  onward must move to close these output gaps. The sum then adds up all these intertemporal shifting effects from past real rate news.<sup>27</sup>

<sup>26</sup>News occur either because the real rate itself is subject to an exogenous shock or because it responds endogenously to one of the other shocks.

<sup>27</sup>In DSGE models,  $r^*$  is often defined in terms of a flexible-price equilibrium. In our equation (5), this corresponds to past interest rates being set equal to the natural rate of interest. In contrast, we compute  $r^*$  based on the realized and expected real interest rate path at each date.

Equation (5) shows that the below-diagonal elements of  $\mathcal{M}$  determine the importance of intertemporal shifting. In our model, these elements are positive because lower real interest rates today borrow aggregate demand from the future. In a standard New Keynesian model, these elements are zero, as past interest rates have no effect on the current or future output gaps. In DSGE models with higher-order adjustment costs, these elements can even be negative, as stimulating investment today reduces the cost of investment tomorrow.

#### 6.4. $r^*$ During and After the Great Recession

The shocks that occurred during the Great Recession imply a substantial and very persistent decline in the natural rate of interest, which drives the model's forecast of low real interest rates. In the left panel of Figure 10, we plot the short-term natural rate of interest implied by our model—that is the first element of  $\vec{r}_t^*$  for each date  $t$ . There is a sharp fall in  $r^*$  in 2008 and 2009. This collapse in  $r^*$  is not surprising as there was indeed a large negative output gap despite low interest rates. The key result in the figure is that  $r^*$  recovers very gradually after the recession. In 2015Q4, when the federal funds rate lifted off from the ELB,  $r^*$  is forecast to be 3.9 percentage points below steady state. Even in 2019Q4,  $r^*$  is 1.9 percentage points below steady state.

$(S, s)$  models can generate nonlinear dynamics that make durable expenditure more sensitive to stimulus in a boom than in a recession (e.g., [Berger and Vavra \(2015\)](#)). In Appendix J of the Online Supplementary Material, we investigate the sensitivity of our results to nonlinear aggregate dynamics such as this. From this investigation, we conclude that our analysis may understate the decline in  $r^*$  during the Great Recession, but the nonlinearities do not have important effects for the medium-run forecasts of  $r^*$  that are our main results.

The figure plots the contribution of intertemporal shifting to  $r^*$ . In 2015Q4, intertemporal shifting accounts for 2.6 percentage points of the decline in  $r^*$ . By the end of the forecast period, nearly all of the decline in  $r^*$  predicted by the model is due to intertemporal shifting.

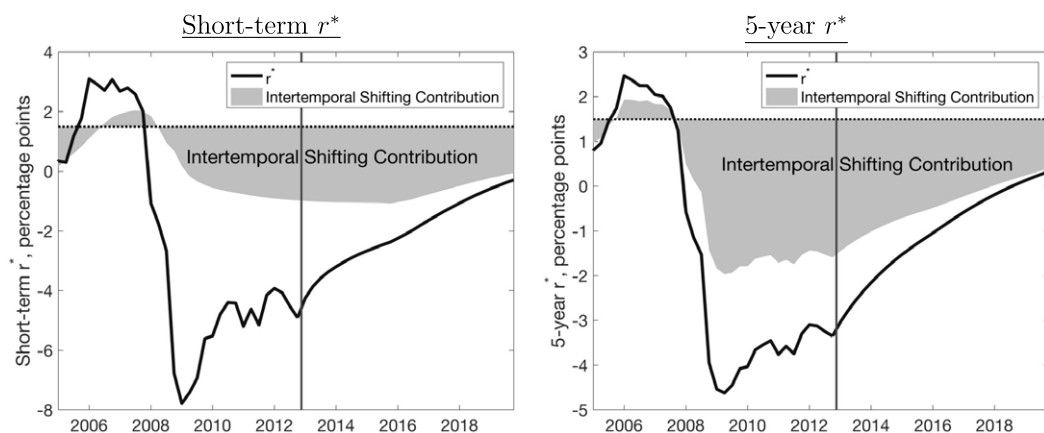


FIGURE 10.—Time series of the short-term natural rate of interest (left panel) and the 5-year natural rate of interest (right panel). The shaded area shows the contribution of intertemporal shifting effects of previous real interest rates to  $r^*$ . Forecast as of 2012Q4. The dotted horizontal line is the steady state real interest rate, equal to 1.5%.

The contribution of intertemporal shifting is nearly constant from 2009 through 2019 for two reasons. First, because of the zero lower bound constraint, the real interest rate path is also almost flat over much of this period and this determines the amount of intertemporal shifting. Second, even after lift off, the model predicts a gradual normalization of interest rates so the contribution of intertemporal shifting only recedes gradually.

In the right panel of Figure 10, we show the 5-year  $r^*$ , computed from expectations of short-term rates using the expectations hypothesis. The 5-year  $r^*$  displays a corresponding large drop and slow normalization. The 5-year  $r^*$  is 2.7 percentage points below steady state in 2015Q4 and 1.2 percentage points below steady state in 2019Q4. Intertemporal shifting largely accounts for the very persistent behavior of these long-term rates.<sup>28</sup> Thus, our model also predicts that medium to long-term rates are significantly impacted by intertemporal shifting long after the end of the Great Recession. These results show the decline in real interest rates during the Great Recession were themselves a key reason that  $r^*$  remained low in subsequent periods.

In Figure 11, we decompose the path for the short-term natural rate of interest into contributions from each shock. This figure shows that shocks differ in their implications for the evolution of  $r^*$ . The figure shows that the real interest rate must fall by almost 7 percentage points to offset the effect of the productivity shock on the output gap. This calculation incorporates both the direct effects of the productivity shock as well as the intertemporal shifting effects from offsetting past productivity shocks. As Figure 11 shows, the productivity shock is particularly important in explaining the persistently low level of  $r^*$ . This is because the productivity shock causes persistent weakness in aggregate demand as households adjust to a lower durable stock. Persistent weakness in demand leads to persistently low interest rates, which in turn generate persistent intertemporal shifting effects leading to continued low real interest rates.

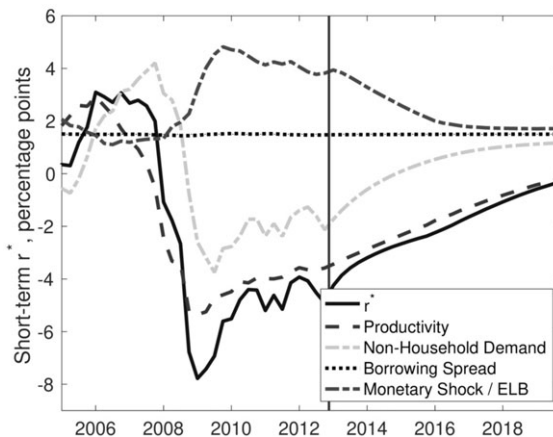


FIGURE 11.—Time series of the short-term natural rate of interest implied by each shock. The blue line is the level of  $r^*$ , the red line is the level of  $r^*$  implied by the productivity shock, the cyan line the is the level of  $r^*$  implied by the non-household demand shock, the black line is the level of  $r^*$  implied by the borrowing spread shock, and the magenta line is the level of  $r^*$  implied by the monetary policy shock and the effective lower bound. Forecasts as of 2012Q4.

<sup>28</sup>To compute the intertemporal shifting contribution to an  $H$ -horizon long-term rate, we solve for the intertemporal shifting contribution to the short rate at  $t, t+1, \dots, t+H$  and average them in accordance with the expectations hypothesis.

During the recession, the decline in real interest rates was limited by the ELB, which we capture as an anticipated contractionary monetary shock. With less monetary accommodation in the recession, there were weaker intertemporal shifting effects leading to a higher path of  $r^*$  going forward as shown in Figure 11.

Comparing the monetary shock to the other shocks in Figure 11, we can see that a recession caused by monetary tightening can cause a persistent increase in  $r^*$ . The Volcker disinflation of the early 1980s is the quintessential example of such a monetary tightening. We can gain a sense of how monetary policy affected  $r^*$  during this period by calculating the response of  $r^*$  to the monetary shocks identified by Romer and Romer (2004). We calculate the real interest rate path implied by the Romer–Romer shocks between 1979Q3 and 1982Q4. These shocks explain half of the total increase in the real interest rate over this period. When we feed these shocks to real interest rates into our model they cause a recession with an output gap that bottoms out at  $-4.2\%$  in 1981Q2. Through the lens of our model, the intertemporal shifting of demand caused by these shocks raised the level of  $r^*$  by 1.3 percentage points on average during 1983 and 1984. For comparison, the average level of the real interest rate during these years was  $6.0\%$ . This calculation suggests that intertemporal shifting effects made a substantial contribution to the elevated level of  $r^*$  during the 1980s. More broadly, this example demonstrates that intertemporal shifting effects do not always predict low interest rates following a recession.

## 7. CONCLUSION

We develop a fixed-cost model of durable consumption demand that is suitable to analyze the monetary transmission mechanism. The model is broadly consistent with both the microeconomic lumpiness of durable adjustments while at the same time consistent with the aggregate response of the economy to changes in interest rates.

Our model predicts that real interest rates will remain low for many years following the Great Recession in line with the realized path of real interest rates. While secular forces may well explain the decline of real interest rates starting in the 1980s, our model provides an alternative explanation for the particularly low interest rates in the 2010s.

The persistence of real interest rates in the model reflects intertemporal shifting of demand for durables. Low real interest rates shift the adjustment thresholds for durables, which induces households to pull forward durable adjustments. As these durable purchases are missing in subsequent periods, interest rates must be kept low to sustain aggregate demand. In this manner, intertemporal shifting effects lead to a slow normalization of  $r^*$  following the Great Recession.

The view we put forward here, in which  $r^*$  responds quite strongly to changes in monetary policy, contrasts with the neo-Wicksellian paradigm, in which  $r^*$  is generally considered to be independent of monetary policy. One implication of our analysis is that monetary accommodation has a side effect of reducing  $r^*$  toward the lower bound implied by the ELB thereby reducing future policy space. While our analysis focuses on a positive description of the economy, the intertemporal shifting of demand we highlight may have important implications for optimal monetary policy.

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*Co-editor Charles I. Jones handled this manuscript.*

*Manuscript received 10 August, 2020; final version accepted 14 May, 2021; available online 2 June, 2021.*