The Mortgage Credit Channel of Macroeconomic Transmission*

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October 16, 2016

Abstract

I investigate the macroeconomic implications of mortgage credit growth in a general equilibrium framework with both a loan-to-value constraint and a limit on the ratio of mortgage payments to income. This realistic structure greatly amplifies transmission from interest rates into debt, house prices, and economic activity. Monetary policy is more effective at stabilizing inflation due to this channel, but contributes to larger fluctuations in credit growth. A relaxation of payment-to-income standards appears essential to the recent boom. A cap on payment-to-income ratios, not loan-to-value ratios, is the more effective macroprudential policy.

1 Introduction

Mortgage debt is central to the workings of the modern macroeconomy. The sharp rise in residential mortgage debt at the start of the twenty-first century in the US and countries around the world has been credited with fueling a dramatic boom in house prices and consumer spending.[1] At the same time, high levels of mortgage debt and household leverage have been blamed for the severity of the subsequent bust, and for the

*This paper is a revised version of Chapter 1 of my Ph.D. dissertation at NYU. I am extremely grateful to my thesis advisors Sydney Ludvigson, Stijn Van Nieuwerburgh, and Gianluca Violante for their invaluable guidance and support. I also thank Adrien Auclert, Gadi Barlevy, Marco Bassetto, Jarda Borovicka, Katka Borovickova, Jeff Campbell, Marco Del Negro, Raquel Fernandez, Andreas Fuster, Xavier Gabaix, Mark Gertler, Francois Gourio, Arpit Gupta, Andy Haughwout, Malin Hu, Alejandro Justiniano, Joseba Martinez, Virgiliu Midrigan, Jan Moller, John Mondragon, Thomas Philippon, Johannes Stroebel, Tom Sargent, Venky Venkateswaran and Paul Willen, as well as seminar audiences for helpful comments that greatly improved the paper. I am indebted to eMBS and Knowledge Decision Services for their generous provision of data. I thank the NYU Dean's Dissertation Fellowship and the Becker-Friedman Institute's Macro Financial Modeling Fellowship for financial support.

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[1] The ratio of household mortgage debt to GDP in the US grew from less than 43% in 1998Q1 to over 73% in 2009Q1 — an increase of nearly 70% (sources: Federal Reserve Board of Governors, Bureau of Economic Analysis).

sluggish nature of the recovery that followed. Since mortgage credit evolves endogenously in response to economic conditions, its critical position in the macroeconomy raises a number of important questions. How, if at all, does mortgage credit growth propagate and amplify macroeconomic fluctuations in general equilibrium? How does mortgage finance affect the ability of monetary policy to influence economic activity? Finally, what role did changing credit standards play in the boom, and how might regulation have limited the resulting bust?

These questions all center on what I will call the *mortgage credit channel* of macroeconomic transmission: the path from primitive shocks, through mortgage credit growth, to the rest of the economy. Characterizing this channel is challenging due to the complex links between mortgage debt and the macroeconomy. Large numbers of heterogeneous households participate in mortgage markets, both as borrowers and savers, trading history-dependent streams of cash flows that differ widely in interest rates. Mortgage contracts are specified in nominal terms, so that real mortgage payments are influenced by inflation. Taking out new mortgage debt is a costly process that typically requires prepayment of existing debt. Households face decisions about whether and when to prepay existing mortgages, and their choices respond endogenously to economic conditions as interest rates and house prices change. New borrowing is constrained by multiple limits determined by endogenous variables such as house prices and income.

In this paper I develop a tractable modeling framework that embeds these features in a New Keynesian dynamic stochastic general equilibrium (DSGE) environment. The framework centers on two key mechanisms that define the mortgage credit channel. First, at the intensive margin, new borrowing is limited by two factors: the ratio of the size of the loan to the value of the underlying collateral ("loan-to-value" or "LTV"), and the ratio of the mortgage payment to the borrower's income ("payment-to-income" or "PTI").[2] While a vast literature documents the impact of LTV constraints on debt dynamics, the influence of PTI limits on the macroeconomy remains relatively unstudied, despite their central role in underwriting in the US and abroad. As I will show, PTI limits fundamentally alter the dynamics of mortgage credit growth, played an essential part in the boom and bust, and are likely to increase further in importance as the centerpiece of new mortgage regulation. Since in a heterogeneous population an endogenous and time-varying fraction of individuals will be limited by each constraint, I develop an aggregation procedure to capture these dynamics at the macro level and calibrate them to match loan-level

[2] The "payment-to-income" (PTI) ratio is also commonly known as the "debt-to-income" or "DTI" ratio. I use the term "payment-to-income" for clarity, since under either name the ratio measures the flow of payments relative to a borrower's income, not the stock of debt relative to a borrower's income.

microdata.

Second, at the extensive margin, borrowers choose whether to prepay their existing loans and replace them with new loans, a process that incurs a transaction cost. This mechanism is designed to capture two empirical facts: only a small minority of borrowers obtain new loans in a given quarter, but the fraction that choose to do so is volatile and highly responsive to interest rate incentives. These dynamics stand in sharp contrast to traditional macro-housing models, in which debt levels mechanically track credit limits, and do not depend directly on interest rates.[3] I develop a tractable method to aggregate over the discrete prepayment decision, which I calibrate to match estimates from a workhorse prepayment model, and show that the endogenous response of prepayment to interest rates is of first-order importance for credit dynamics and transmission.

This framework generates two main sets of findings. The first set relate to interest rate transmission, where I find that the novel features of the model, when calibrated to US mortgage microdata, greatly amplify transmission from interest rates in to debt, house prices, and economic activity. The first step in the transmission chain is that PTI limits are themselves highly sensitive to interest rates, moving by roughly 10% in response to a 1% shift in nominal rates. But because only a minority of borrowers are constrained by PTI at equilibrium, this would not by itself be able to generate large aggregate effects. Instead, the key is a novel propagation mechanism through which changes in which of the two constraints is binding for borrowers translates into large movements in house prices, which I call the *constraint switching effect*. This effect is quantitatively powerful, leading a 1% fall in nominal rates to cause price-rent ratios to rise by more than 4%. This rise in house prices in turn loosens borrowing constraints for the LTV-constrained majority of the population, leading to nearly twice the increase of credit growth relative to an alternative economy with an LTV constraint only (7.9% vs. 4.7% at 20Q).

For transmission into output, however, it turns out that the endogenous prepayment option of borrowers is critical, due to its influence on timing. When borrowers have the option to prepay, a fall in rates leads to a wave of prepayments, new issuance, and new spending on impact, generating a large output response — a phenomenon I call the *front-loading effect*. Quantitatively, this effect increases the impact of a 1% technology shock on output by more than half (0.50% to 0.76%). Counterfactuals without endogenous prepayment generate much slower issuance of credit with virtually zero effect on output,

[3] The traditional uses one period debt and assumes that borrowers are always at their constraint, so that debt is equal to the debt limit at all times. Improvements such as adjustments to borrowing limits to account for "ratchet effects" (e.g., Justiniano, Primiceri, and Tambalotti (2015)) are more realistic still imply that debt is a mechanical function of past debt limits.

despite a similar increase in debt limits. These results on transmission have important implications for monetary policy, which is more effective at stabilizing inflation due to these forces, but contributes to larger swings in credit growth, posing a potential trade-off for central bankers worried about stabilizing both markets.

The second set of findings relate to credit standards and the sources of the recent boom and bust, where I find that a relaxation of PTI limits were essential. Although much of the literature to date has focused on changes in LTV constraints as a potential cause of the boom, I find that a relaxation of LTV standards alone could not have created the observed boom if PTI constraints had been held fixed at their historical standards. In contrast, an experiment calibrated to empirical evidence showing massive relaxation of PTI standards generates a realistic boom accounting for nearly half of the observed increase in price-rent ratios 38% and debt-to-household-income (47%) ratios.

These results have important implications for macroprudential policy, implying that a regulatory cap on PTI ratios, not LTV ratios, is the more effective macroprudential policy. In particular, I am able to evaluate the effect of the Dodd-Frank regulations, whose main mortgage market reform was to introduce, for the first time, a legal limit on PTI ratios. While the Dodd-Frank cap is still somewhat loose compared to historical norms, I show that it would have nonetheless been effective during the boom, reducing the rise in price-rent ratios by nearly two-thirds compared to a counterfactual liberalizing both LTV and PTI ratios.

Literature Review

This paper builds on several existing strands of the literature.[4] The first is a large and growing body of empirical work demonstrating important links between mortgage credit, house prices, and economic activity.[5] This study complements these works by studying the theoretical mechanisms behind many of these links in general equilibrium.

Turning to theoretical models, the literature can be broadly split into two camps. The first are heterogeneous agent models, often with rich specifications of idiosyncratic risk, costly financial transactions, and long-term mortgage contracts, but that cannot tractably to consider inflation, monetary policy, and endogenous output in general equilibrium.[6]

[4]See Davis and Van Nieuwerburgh (2014) for a survey of the recent literature on housing, mortgages, and the macroeconomy.

[5]See Mian and Sufi (2008), Aladangady (2014), Mian and Sufi (2014), Adelino, Schoar, and Severino (2015a), Adelino, Schoar, and Severino (2015b), Adelino, Schoar, and Severino (2015c), Di Maggio and Kermani (2015), Favara and Imbs (2015).

[6]Works include Favilukis, Kohn, Ludvigson, and Van Nieuwerburgh (2012), Kermani (2012), Chen, Michaux, and Roussanov (2013), Corbae and Quintin (2013), Khandani, Lo, and Merton (2013), Laufer (2013), Favilukis, Ludvigson, and Van Nieuwerburgh (2014), Guler (2014), Kaplan, Violante, and Wei-

In contrast, a set of monetary DSGE models with housing and collateralized debt can easily handle these macroeconomic features, but use simplified loan strutures that cannot capture certain features of debt dynamics.[7] In this paper I seek to combine these two approaches, embedding a realistic mortgage structure in a tractable general equilibrium environment.

Moreover, to my knowledge, Corbae and Quintin (2013) is the only other macroeconomic model to incorporate a PTI constraint and to use its relaxation as a proxy for the housing boom. However, these authors use the PTI constraint as a means to explore the relationship between endogenously priced default risk and credit growth in a model with exogenous house prices. While this setup delivers important findings regarding default and foreclosure, both absent from my model, it does not study the influence of the PTI constraint on macroeconomic dynamics, or, through its influence on house prices, on the LTV constraint, the key to the results of this paper.

This paper is also related to models connecting a relaxation of credit standards to the recent boom-bust.[8] My findings largely support the importance of credit liberalization in the boom, with the specific twist that a relaxation of PTI constraints appears key. Of particular relevance in this line of work is Justiniano et al. (2015), who find that the interaction of an LTV constraint with an exogenous lending limit can generate strong effects of movements in the non-LTV constraint on debt and house prices — a result echoed in many of the findings of this paper. By utilizing an endogenous PTI constraint in place of an exogenous fixed limit on lending, I am able to connect these dynamics to interest rate transmission, link observed relaxations of PTI standards in the data, and analyze the effects of the regulatory cap on PTI limits imposed by Dodd-Frank.

Finally, this work parallels research on the *redistribution channel* of monetary policy.[9] When borrowers hold adjustable-rate mortgages, changes in interest rates lead to changes in payments on the existing stock of debt, potentially stimulating spending. While potentially important, the redistribution channel is distinct from, and complementary to, the mortgage credit channel, which operates instead through changes in the flow of new credit driven by changes in borrowing constraints.[10]

dner (2014), Campbell and Cocco (2015), Chatterjee and Eyigungor (2015), Elenev, Landvoigt, and Van Nieuwerburgh (2015), Gorea and Midrigan (2015), Landvoigt (2015).

[7] See Iacoviello (2005), Monacelli (2008), Iacoviello and Neri (2010), Ghent (2012), Liu, Wang, and Zha (2013), Rognlie, Shleifer, and Simsek (2014).

[8] See Campbell and Hercowitz (2005), Iacoviello and Pavan (2013), Favilukis, Ludvigson, and Van Nieuwerburgh (2015), Garriga, Kydland, and Sustek (2015).

[9] See Rubio (2011), Calza, Monacelli, and Stracca (2013), Auclert (2015).

[10] Perhaps surprisingly, while allowing borrowers to prepay their loans does allow for substantial changes in payments when interest rates fall, and therefore large redistributions between borrowers and savers, the redistribution channel is nonetheless weak in my framework, leading to very small aggregate stimulus.

Overview

The remainder of the paper is organized as follows. Section 2 describes LTV and PTI constraints and their empirical properties, and provides a numerical example. Section 3 constructs the theoretical model. Section 4 derives the optimality conditions and describes the calibration procedure. Section 5 presents the results on interest rate transmission, and the impact on monetary policy. Section 6 discusses the role of credit standards in the boom-bust, and the implications for macroprudential policy. Section 7 concludes. Additional results and extensions can be found in the appendix.

2 Background: LTV and PTI Constraints

This section presents a simple numerical example, and demonstrates the empirical properties of LTV and PTI limits in the data.

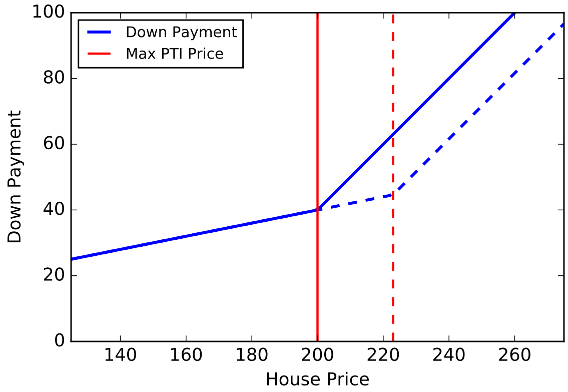
2.1 Simple Numerical Example

To provide intuition for the core mechanisms of the model, I present a simplified example from an individual borrower's perspective. Consider a prospective home-buyer who prefers borrowing to paying in cash today, perhaps because she must save for the down payment and delaying purchase is costly. Assume that the borrower's income is \$50k per year, and that she faces a 28% PTI limit, meaning that she can put at most \$1.2k per month toward her mortgage payment.[11] At an interest rate of 6%, this maximum payment is associated with a loan size of \$160k, which is the most she can borrow subject to her PTI limit. Her maximum LTV ratio is 80%, which requires her to pay a minimum of 20% of the value of the house in down payment. Adding a minimum the 20% down payment to this balance delivers a house price of \$200k, which represents the price at which the borrower switches from being LTV-constrained to PTI-constrained.

This switch creates a kink in the borrower's required down payment as a function of house prices, shown as the solid blue line in Figure 1. Below this price, the borrower is constrained by the value of her collateral, so increasing her house value by \$1 allows her to borrow an additional 80 cents, requiring her to put only 20 cents down. But above the kink, she is constrained by her income and cannot obtain any more debt no matter

The key is the persistence of the change, as the fixed-rate-mortgage structure induces a near-permanent transfer between the two groups. See Section A.6 of the appendix for details.

[11]For this example, I abstract from taxes, insurance, and non-mortgage debt payments, and round all figures to the nearest \$1k = \$1,000.



(a) Interest Rate ↓ or PTI Ratio ↑

(b) LTV Ratio ↑

Figure 1: Simple Example: House Price vs. Down Payment

the value of her collateral, and must pay dollar for dollar in cash for additional housing beyond this point. This discrete change implies that a house price of exactly $200k is a likely optimum for this borrower, and for the sake of the example, let us assume that this is indeed her choice.

From this starting point, imagine that the mortgage interest rate now falls from 6% to 5%, displayed graphically as the dashed lines in Figure 1a. While the borrower's maximum monthly payment has not changed, at a lower interest rate this payment is now associated with a loan of size $178k, and a kink house price of $223k, an increase of 11% in each variable. If the borrower once again follows her corner solution, this will cause a large increase in her housing demand, potentially leading to a substantial rise in house prices if many borrowers do the same. For intuition, after the fall in rates the borrower is now eligible for a larger loan, but in order to collateralize this loan, she needs a larger house. This drives borrowers to demand larger and more valuable houses, pushing up the demand for collateral, and the price of housing.

This example can also be used to analyze changes in credit standards. First, consider an increase in allowed PTI ratios. Since this intervention increases the maximum PTI loan size, the impact on the down payment function is identical to the fall in the interest rate. Specifically, a rise from a 28% to a 31% PTI ratio exactly replicates the change in Figure 1a, once again raising the kink house price, and potentially boosting housing demand. In contrast, increasing the maximum LTV ratio from 80% to 90%, shown in Figure 1b, has a sharply different impact. While the borrower's maximum loan size under given her income remains at $160k, the house price at which her loan reaches this limit decreases to $178k (an 11% decrease). This occurs because a less costly house is now sufficient to collateralize the same amount of debt. If borrowers still choose their corner solution, this implies that an increase in the LTV limit should actually cause house prices to *fall*.

To understand this result, note that prior to the LTV loosening, moving from a $200k house to a $178k house would only have let the borrower keep $4.4k in cash, since she would have been forced to cut her loan size. But after the relaxation, the borrower can keep the entire $22k difference in cash, making downsizing much more tempting. Another way to view this finding is that a relaxation of the LTV limit increases the supply of collateral (since each unit of housing can collateralize more debt), but not the demand for collateral (since the borrower's overall loan size has not increased), decreasing the value of collateral at equilibrium. This result stands in stark contrast to models in which borrowers face only an LTV constraint, where lower down payments tend to increase housing demand and house prices.

2.2 LTV and PTI in the Data

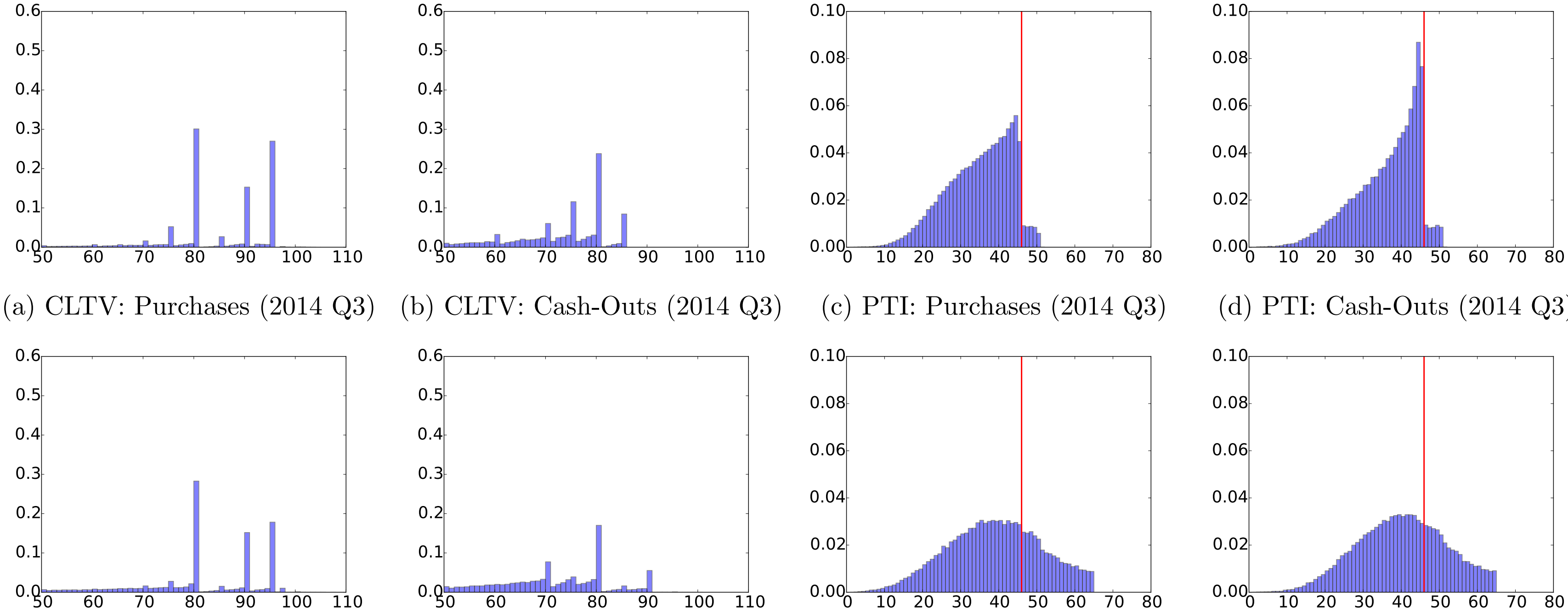
This section considers the empirical properties of the LTV and PTI constraints.[12] Figure 2 shows the distribution of combined LTV (CLTV) and PTI on newly issued Fannie Mae loans in two periods: the height of the boom (2006 Q1) and a recent datapoint (2014 Q3).[13] First, let us consider the plots for 2014, which are likely to be indicative of lending standards going forward, beginning with purchase loans.[14] Figure 2a shows that the CLTV ratios on purchase loans display very clear spikes at well-known institutional limits: the 80% private mortgage insurance threshold, as well as higher institutional thresholds at 90% and 95%, indicating clear influence of LTV limits on borrowing behavior.

In contrast, a different pattern can be observed for PTI ratios on purchase loans, as shown in Figure 2c. In this case, instead of a single spike at the institutional limit of 45%, the data instead display what looks like a truncated distribution, gradually building up in density until a massive drop-off after the threshold. What behavior generates this pattern? An intuitive explanation is that borrowers who are PTI constrained would like to buy a house that corresponds to the maximum loan size under PTI, plus the minimum

[12] See Section A.2 in the appendix for more on the institutional details of these constraints.

[13] Combined LTV accounts for the possibility that the borrower may have multiple mortgages against the same property, and is the ratio of total debt on all loans relative to the value of the house.

[14] Purchase loans are used to buy a new property, in contrast to a refinance, in which a new loan is issued for the same property. Refinances are further split into "cash-out" and "no-cash-out" varieties, the difference being that in a cash-out refinance the balance on the loan is increased, whereas under a "no-cash-out" refinance, the balance is unchanged — an option typically used to change the interest rate on the loan.



(a) CLTV: Purchases (2014 Q3)
(b) CLTV: Cash-Outs (2014 Q3)
(c) PTI: Purchases (2014 Q3)
(d) PTI: Cash-Outs (2014 Q3)
(e) CLTV: Purchases (2006 Q1)
(f) CLTV: Cash-Outs (2006 Q1)
(g) PTI: Purchases (2006 Q1)
(h) PTI: Cash-Outs (2006 Q1)

Figure 2: Fannie Mae: PTI on Newly Originated Mortgages

Note: Histograms are weighted by loan balance. Source: Fannie Mae Single Family Dataset.

down payment, which is the kink price of Section 2.1. However, due to an imperfect search process, borrowers may not be able to find a house with exactly this value. Since going above this threshold requires paying dollar-for-dollar in down payment, borrowers may be more willing to settle for a house that is below, rather than above, this threshold.[15]

If a borrower pursues this strategy, she will end up with a house valued at or slightly below her kink price, putting her slightly below the PTI constraint. Since she ends up in the LTV constrained region as a result, if she gets the largest loan possible she end up at one of the LTV limits, and exactly reproducing the observed patterns. If this explanation is correct, it implies that many, though probably not most, borrowers are influenced by PTI, even though there is no spike in the final bin before the constraint.[16]

While more empirical work is required to verify this conjecture, one supportive piece of evidence comes from the distributions of CLTV and PTI ratios on cash-out refinances. In a cash-out refinance, a borrower does not purchase a new home, but instead obtains a new loan for her existing home. In this case, there should be no search frictions, and a constrained borrower should simply borrow up to her LTV or PTI limit, whichever is lower. In this case, we should expect to see more bunching at the PTI threshold relative to purchase loans, which is indeed the case comparing Figure 2d to Figure 2c. Further, we should see *less* bunching at institutional LTV limits — since borrowers can no longer choose the house value to ensure it is below the threshold — which again is confirmed by comparison of Figure 2b to Figure 2a, with much more mass between spikes for cash-out loans.

The empirical patterns during the recent housing boom differ strikingly from this recent sample. From Figure 2g, we observe that PTI ratios on purchase loans during the boom period (2006 Q1) do not appear to be limited by any institutional constraint, with many borrowers taking on extremely high PTI ratios.[17] These plots are suggestive of very loose PTI standards during the housing boom. No limit is visible even in the the distribution of cash-out refinance mortgages (2h) which showed so much bunching in 2014. In contrast, the distribution of CLTV ratios do not appear remarkably different, implying that the more dramatic shift occurred in PTI limits. [18]

[15]In fact, many banks may preapprove borrowers for exactly this threshold amount by default, making it difficult for borrowers to even make an offer on a house above this threshold price.

[16]For intuition, the reason why LTV and PTI ratios have different observed distributions despite similar institutional limits on each ratio is that it is easier for borrowers to select the size of the house that they purchase than their income or the interest rate.

[17]The cutoff at 65% is a top-coding by the data provider.

[18]Further evidence for this shift in PTI standards can be found in Figure A.2 of the appendix, which shows the evolution of quantiles of the PTI ratios on purchase loans for the period 2000-2014. The data show a substantial rise and fall in PTI ratios over the boom-bust. In fact, these plots only capture part of the increase in PTI ratios, which began in the mid-1990s. Using Fannie Mae data, Pinto (2011)

3 Model

This section constructs the theoretical model, derives aggregation from individuals to representative agents, and presents the representative agents' optimization problems.

3.1 Demographics and Preferences

The economy consists of two families, each populated by a continuum of infinitely-lived households. The households in each family differ in their preferences: one family contains relatively impatient households named "borrowers" and denoted with subscript b, while the other family contains relatively patient households named "savers" and denoted with subscript s. The measures of the two populations are χ_b and $\chi_s = 1 - \chi_b$, respectively. Households can trade a complete set of contracts for consumption and housing services among households within their own family, providing complete insurance against idiosyncratic risk, but cannot trade these securities with members of the other family. Both types supply perfectly substitutable labor and consume housing and a single nondurable consumption good.

Each agent of type $j \in \{b, s\}$ maximizes expected lifetime utility over nondurable consumption $c_{j,t}$, housing $h_{j,t}$, and labor supply $n_{j,t}$:

$$V_{j,t} = \mathbb{E}_t \sum_{k=0}^{\infty} \beta_j^k u(c_{j,t+k}, h_{j,t+k}, n_{j,t+k}). \tag{1}$$

Utility takes the separable form

$$u(c, n, h) = \log(c) + \xi \log(h) - \eta \frac{n^{1+\varphi}}{1+\varphi} \tag{2}$$

Preference parameters are identical across types with the exception that $\beta_b < \beta_s$, so that borrowers are less patient than savers. For notation, define the marginal utility and stochastic discount factor for each type by

$$u^c_{j,t} = \frac{\partial u(c_{j,t}, n_{j,t}, h_{j,t})}{\partial c_{j,t}} \qquad\qquad \Lambda_{j,t+1} = \beta_j \frac{u^c_{j,t+1}}{u^c_{j,t}}$$

with symmetric expressions for $u^n_{j,t}$ and $u^h_{j,t}$.

calculates that the 75th percentile of the PTI distribution over the period 1988-1991 was below 36%. As shown in Figure A.2d, by 2000, the 75th percentile has already reached 42%, and eventually peaks at 49%, meaning that one in four borrowers was pledging half of his or her gross income toward their debt payments. In contrast, CLTV ratios appear largely flat over the boom, suggesting a less sharp change in LTV standards relative to PTI standards.[19]

3.2 Asset Technology

For notation, starred variables (e.g., q_t^*) denote values at origination (i.e., for a *new* loan), which will be used to distinguish from the corresponding values for *existing* loans in the economy — a distinction necessary under long-term fixed-rate debt. A dollar sign "\$" before a quantity implies that it is measured in nominal terms.

3.2.1 One-Period Bonds

There is a one-period nominal bond, whose balances are denoted b_t, in zero net supply. One unit of this bond costs \$1 at time t and pays $\$R_t$ with certainty at time $t+1$. Since the focus of the paper is on mortgage debt, I assume that positions in the one-period bond must be non-negative, so that this bond cannot be used for borrowing. As a result, this bond is traded at equilibrium by the saver only, and serves to provide the monetary authority with a policy instrument.

3.2.2 Mortgages

Mortgages, whose balances are denoted m_t, are the essential financial asset in this paper, and the only source of borrowing in the model economy.

Cash Flows

The mortgage is modeled as a nominal perpetuity with geometrically declining payments, as in Chatterjee and Eyigungor (2015). I consider a fixed-rate mortgage contract, which is the predominant contract in the US, but extend the model for the case of adjustable-rate mortgages in the appendix. The fixed-rate mortgage's cash flows occur as follows. At origination, the saver gives the borrower \$1. In exchange, the saver receives $\$(1-\nu)^k q_t^*$ at time $t+k$, for all $k>0$ until prepayment, where q_t^* is the equilibrium coupon rate at origination, and ν is the fraction of principal paid each period. Let q_t define the average coupon rate on all debt at time t, and let $x_t = q_t m_t$ denote the average payment.

Prepayment

As is standard in US mortgage contracts, the borrower can choose to repay the principal balance on a loan at any time, which cancels all future payments of the loan. If a borrower chooses to prepay her loan, she may choose a new house size $h_{i,t}^*$ and a new loan size $m_{i,t}^*$ subject to her credit limits (defined below).

Obtaining a new loan requires the borrower to pay a transaction cost $\kappa_{i,t}m^*_{i,t}$, where $\kappa_{i,t}$ is drawn i.i.d. across individual members of the family and across time from a distribution with c.d.f. Γ_κ. This heterogeneity in costs is natural to the discrete choice nature of the problem: in order to match the data, otherwise identical model borrowers must make different decisions so that only a fraction prepay in each period. The borrower's optimal policy is to prepay the loan if and only if her cost $\kappa_{i,t}$ is below some threshold value $\bar{\kappa}_t$, which therefore completely characterizes prepayment policy.

To allow for aggregation, I make a simplifying assumption: that borrowers are allowed to choose their prepayment policy $\bar{\kappa}_t$ based only on aggregate states, and not on the characteristics of their individual loans. This implies that the probability of prepayment is constant across borrowers at any single point in time.[20] While this abstracts from some of the cross-sectional dynamics of prepayment, note that the prepayment rate in the simplified economy can still endogenously respond to key economic conditions such as the difference between existing and new interest rates, and the amount of home equity available to be extracted.[21]

Borrowing Limits

A new loan for borrower i must satisfy both a LTV and PTI constraint, defined by

$$\frac{m^*_{i,t}}{p^h_t h^*_{b,t}} \leq \theta^{ltv}, \qquad\qquad \frac{(q^*_t + \tau)m^*_{i,t}}{w_t n_{i,t} e_{i,t}} + \omega \leq \theta^{pti}.$$

where $m^*_{i,t}$ is the balance on the new loan, and θ^{ltv} and θ^{pti} are the maximum LTV and PTI ratios, respectively. The LTV ratio is simply the ratio of the loan balance to the borrower's house value. For the PTI ratio, the numerator is the borrower's initial payment, where τ is an adjustment for property taxes, insurance, and servicing costs, while the denominator is the borrower's labor income, given as the product of the wage w_t, labor supply $n_{i,t}$, and an idiosyncratic labor efficiency shock $e_{i,t}$, drawn i.i.d. across borrowers and time with c.d.f. Γ_e. This income shock serves to generate variation among borrowers, so that an endogenous fraction are limited by each constraint at equilibrium.[22] Finally, the offsetting term ω is to adjust for the fact that PTI is typically measured as

[20] This assumption is equivalent to having the borrowers pool their loans into a single loan with average balance and interest rate at the end of each period.

[21] Since I calibrate to match the average prepayment rate and prepayment sensitivity to interest rates, I should be able to eliminate bias due to this assumption on average. As a result, bias should only come from ignoring time variation in the shape of the distribution of interest rates and maturities.

[22] While I model $e_{i,t}$ as an income shock, it could stand in for any shock that varies the house price-to-income ratio in the population. Without variation in this ratio, all borrowers would be limited by the same constraint in a given period.

total recurring debt payments, including payments on car loans, student loans, etc, which I assume to require a fixed fraction of borrower income.[23] These expressions imply the maximum debt balances

$$\bar{m}^{ltv}_{i,t} = \theta^{ltv} p^h_t h^*_{i,t}, \qquad\qquad \bar{m}^{pti}_{i,t} = \frac{(\theta^{pti} - \omega) w_t n_{i,t} e_{i,t}}{q^*_t + \tau}$$

consistent with each of the two constraints. Since the borrower must satisfy both constraints, her overall debt limit is $m^*_t \leq \bar{m}_{i,t} = \min(\bar{m}^{ltv}_{i,t}, \bar{m}^{pti}_{i,t})$.

3.2.3 Housing

Both borrowers and savers own housing, which produces a flow of housing services each period equal to the stock. I fix the total housing stock to be $\bar{H}$, which greatly simplifies the analysis, and implies that house prices can now capture all movements in the housing market.[24] Fraction δ of each unit of housing depreciates each period, and must be replaced by an equal quantity of new housing, paid as a maintenance cost. Borrower and saver stocks of housing are denoted $h_{b,t}$ and $h_{s,t}$, respectively. To focus on the use of housing as a collateral asset, I assume that saver demand is independently fixed at $h_{s,t} = \bar{H}_s$, so that a borrower is always the marginal buyer of housing.[25] Finally, as is standard in the US, an individual loan is tied to a specific property in the model, and so households cannot adjust their housing stock without prepaying their loan.

3.3 Representative Borrower's Problem

As proved in the appendix, the individual borrower's problem aggregates to that of a single representative borrower. The endogenous state variables for the representative borrower's problem are the total start-of-period debt balance m_{t-1}, total start-of-period borrower housing $h_{b,t-1}$, and the total promised payment on existing debt x_{t-1}. If we define $\rho_t = \Gamma_\kappa(\bar{\kappa}_t)$ to be the fraction of loans prepaid, then the laws of motion for these

[23] Since the dynamics of other debt are beyond the scope of this paper, I assume this debt is owed to other borrowers, so that it has no other influence beyond this constraint.

[24] The assumption that the housing stock is fixed abstracts from the important role played by residential investment in the economy, and implies that price effects should be considered as an upper bound on the true impact. However, from the perspective of credit growth, larger changes in house price under the fixed stock should largely compensate for movements in quantity in determining the total value of housing collateral, which is of primary importance in this setting. Finally, results in terms of price-rent ratios, which I focus on for evaluation of the boom-bust, should not be strongly affected by this choice.

[25] The fixed saver demand can be equivalently interpreted as segmented housing markets among borrowers and savers. In this case, the overall house price in the model corresponds to the price of borrower housing.

state variables are defined by

$$m_t = \rho_t m_t^* + (1-\rho_t)(1-\nu)\pi_t^{-1} m_{t-1} \tag{3}$$

$$h_{b,t} = \rho_t h_{b,t}^* + (1-\rho_t) h_{b,t-1} \tag{4}$$

$$x_t = \rho_t q_t^* m_t^* + (1-\rho_t)(1-\nu)\pi_t^{-1} x_{t-1} \tag{5}$$

The representative borrower chooses consumption $c_{b,t}$, labor supply $n_{b,t}$, the size of newly purchased houses $h_{b,t}^*$, the face value of newly issued mortgages m_t^*, and the fraction of loans/houses to prepay ρ_t to maximize (1) using the aggregate utility function[26]

$$u(c_{b,t}, h_{b,t-1}, n_{b,t}) = \log(c_{b,t}/\chi_b) + \xi \log(h_{b,t-1}/\chi_b) - \eta \frac{(n_{b,t}/\chi_b)^{1+\varphi}}{1+\varphi}$$

subject to the budget constraint

$$\begin{aligned} c_{b,t} \leq{} & w_t n_{b,t} - \pi_t^{-1} x_{t-1} + \rho_t \left(m_t^* - (1-\nu)\pi_t^{-1} m_{t-1} \right) \\ & - \delta p_t^h h_{b,t-1} - \rho_t p_t^h \left(h_{b,t}^* - h_{b,t-1} \right) - \left(\text{Cost}(\rho_t) - \text{Rebate}_t \right) m_t^* \end{aligned}$$

the debt constraint

$$\bar{m}_t = \underbrace{\bar{m}_t^{pti} \int^{\bar{e}_t} e_i \, d\Gamma_e(e_i)}_{\text{PTI Constrained}} + \underbrace{\bar{m}_t^{ltv} (1 - \Gamma_e(\bar{e}_t))}_{\text{LTV Constrained}}. \tag{6}$$

and the laws of motion (3) - (5), where

$$\bar{m}_t^{ltv} = \theta^{ltv} p_t^h h_{b,t}^* \qquad\qquad \bar{m}_t^{pti} = \frac{(\theta^{pti} - \omega) w_t n_{b,t}}{q_t^* + \tau}$$

are the population average LTV and PTI limits, $\bar{e}_t = \bar{m}_t^{ltv} / \bar{m}_t^{pti}$ is the threshold value of the income shock $e_{i,t}$ so that for $e_{i,t} < \bar{e}_t$, borrowers are constrained by PTI,

$$\text{Cost}(\rho_t) = \int^{\Gamma^{-1}(\rho_t)} \kappa d\Gamma_\kappa(\kappa)$$

is the average cost per unit of issued debt, and Rebate_t is a proportional rebate that returns the resource cost $\text{Cost}(\rho_t)$ to borrowers.[27]

[26]This is identical to (2) with the exception that the division by χ_b puts the aggregate variables in per-capita terms.

[27]Similar to the approach in Garriga et al. (2015), I choose to rebate these costs to borrowers, out of consideration that these costs may stand in for non-monetary frictions in refinancing such as inertia.

3.4 Saver's Problem

Just as in the borrower case, the individual saver's problem aggregates to that of a representative saver. The representative saver chooses consumption $c_{s,t}$, labor supply $n_{s,t}$, and the face value of newly issued mortgages m_t^* to maximize (1) using the utility function

$$u(c_{s,t}, h_{s,t-1}, n_{s,t}) = \log(c_{s,t}/\chi_s) + \xi \log(h_{s,t-1}/\chi_s) - \eta \frac{(n_{s,t}/\chi_s)^{1+\varphi}}{1+\varphi}$$

subject to the budget constraint

$$\begin{aligned} c_{s,t} \leq \Pi_t + w_t n_{s,t} - \rho_t(m_t^* - (1-\nu)\pi_t^{-1} m_{t-1}) + \pi_t^{-1} x_{t-1} \\ - \delta p_t^h \bar{H}_s - R_t^{-1} b_t + b_{t-1} \end{aligned}$$

and the laws of motion (3), (5), where Π_t are intermediate firm profits. The saver takes the fraction of loans prepaid ρ_t as given, since this is chosen by the borrower.[28]

3.5 Productive Technology

The production side of the economy is populated by a continuum of intermediate goods producers and a final good producer.

3.5.1 Final Good Producer

The final good producer solves the static problem

$$\max_{y_t(i)} P_t \left[\int y_t(i)^{\frac{\lambda-1}{\lambda}} \, di \right]^{\frac{\lambda}{\lambda-1}} - \int P_t(i) y_t(i) \, di$$

where each input $y_t(i)$ is purchased from an intermediate good producer at price $P_t(i)$, and P_t is the price of the final good.

3.5.2 Intermediate Goods Producers

Intermediate producers owned by the savers choose price $P_t(i)$ and operate the linear production function

$$y_t(i) = a_t n_t(i)$$

[28] For a fixed ρ_t, next period's mortgage holdings m_t are uniquely pinned down by m_t^*, so that m_t^* is an appropriate control variable for the saver's problem.

to meet the final good producer's demand for good i given that price, where $n_t(i)$ represents labor demand and a_t is total factor productivity, which follows the stochastic process

$$\log a_{t+1} = (1-\phi_a)\mu_a + \phi_a \log a_t + \varepsilon_{a,t+1}, \qquad \varepsilon_{a,t} \sim N(0, \sigma_a^2).$$

Intermediate firms are subject to price stickiness of the Calvo-Yun form with indexation. Specifically, a fraction $1-\zeta$ of firms are able to adjust their price each period, while the remaining fraction ζ update their existing price by the rate of steady state inflation.

3.6 Monetary Policy

The central bank follows a Taylor rule similar to that of Smets and Wouters (2007) of the form

$$\begin{aligned} \log R_t = \log \bar{\pi}_t &+ \phi_r(\log R_{t-1} - \log \bar{\pi}_{t-1}) \\ &+ (1-\phi_r)\Big[(\log R^{ss} - \log \pi^{ss}) + \psi_\pi(\log \pi_t - \log \bar{\pi}_t)\Big] \end{aligned} \tag{7}$$

where the superscript "ss" refers to steady state values, where $\bar{\pi}_t$ is a time-varying inflation target defined by

$$\log \bar{\pi}_t = (1-\psi_{\bar{\pi}}) \log \pi^{ss} + \psi_{\bar{\pi}} \log \bar{\pi}_{t-1} + \varepsilon_{\bar{\pi},t}, \qquad \varepsilon_{\bar{\pi},t} \sim N(0, \sigma_{\bar{\pi}}^2).$$

These shocks to the inflation target are near-permanent shocks to monetary policy, and as in Garriga et al. (2015), can be interpreted as "level factor" shocks that shift the entire term structure of nominal interest rates. In the simple bond-pricing environment of this paper, with no important source of term premia or risk premia, these shifts in long-run inflation expectations are needed for monetary policy to move long rates. In the limit $\psi_\pi \to \infty$, the rule (7) collapses to

$$\pi_t = \bar{\pi}_t \tag{8}$$

corresponding to the case of perfect inflation stabilization, which implicitly defines the value of R_t needed to attain equality.

3.7 Equilibrium

A competitive equilibrium in this model is defined as a sequence of endogenous states (m_{t-1}, x_{t-1}), allocations $(c_{j,t}, n_{j,t})$, mortgage and housing market quantities $(h_{b,t}^*, m_t^*, \rho_t)$, and prices $(\pi_t, w_t, p^h_t, R_t, q^*_t)$ such that:

1. Given prices, $(c_{b,t}, n_{b,t}, h^*_{b,t}, m^*_t, \rho_t)$ solve the borrower's problem.

2. Given prices and borrower refinancing behavior, $(c_{s,t}, n_{s,t}, m^*_t)$ solve the saver's problem.

3. Given wages and consumer demand, π_t is the outcome of the intermediate firm's optimization problem.

4. Given inflation and output, R_t satisfies the monetary policy rule (7).

5. The resource market clears:

$$y_t = c_{b,t} + c_{s,t} + \delta\bar{H}.$$

6. The bond market clears: $b_{s,t} = 0$.

7. The housing markets clear: $h_{b,t} + \bar{H}_s = \bar{H}$.

This completes the model description.

4 Model Solution and Calibration

This section derives and discusses the optimality conditions for the model, and describes the calibration procedure.

4.1 Borrower Optimality

Optimality of labor supply, $n_{b,t}$, implies the intratemporal condition

$$-\frac{u^n_{b,t}}{u^c_{b,t}} = w_t + \mu_t\rho_t\left(\frac{(\theta^{pti} - \omega)w_t}{q^*_t + \tau}\right)\int^{\bar{e}_t} e_i \, d\Gamma_e(e_i). \tag{9}$$

where the second term on the right accounts for the borrower's incentive to relax the PTI constraint by working more.[29] Optimality of new debt, $m^*_{i,t}$, requires

$$1 = \Omega^m_{b,t} + q^*_t\Omega^x_{b,t} + \mu_t \tag{10}$$

[29]Because I assume that the borrower chooses her labor supply before deciding whether to prepay, this has a very small effect on labor supply, equivalent to a 2.5% increase in wages in steady state. Results assuming that borrowers do not internalize the effect of their labor supply decision on their credit availability, which sets this term to zero, are virtually identical.

where μ_t, the multiplier on the borrower's aggregate credit limit, and $\Omega^m_{b,t}$ and $\Omega^x_{b,t}$ are the marginal continuation costs to the borrower of taking on an additional dollar of face value debt, and of promising an additional dollar of initial payments, defined by

$$\Omega^m_{b,t} = \mathbb{E}_t \left\{ \Lambda_{b,t+1}\pi^{-1}_{t+1} \left[(1-\nu)\rho_{t+1} + (1-\nu)(1-\rho_{t+1})\Omega^m_{b,t+1} \right] \right\} \tag{11}$$

$$\Omega^x_{b,t} = \mathbb{E}_t \left\{ \Lambda_{b,t+1}\pi^{-1}_{t+1} \left[1 + (1-\nu)(1-\rho_{t+1})\Omega^x_{b,t+1} \right] \right\} \tag{12}$$

respectively.

Turning to the borrower's choice of housing, the optimality condition is

$$p^h_t = \frac{\mathbb{E}_t \left\{ u^h_{b,t+1}/u^c_{b,t+1} + \Lambda_{b,t+1} p^h_{t+1} \left[1 - \delta - (1-\rho_{t+1})\mathcal{C}_{t+1} \right] \right\}}{1 - \mathcal{C}_t} \tag{13}$$

where

$$\mathcal{C}_t = \mu_t F^{ltv}_t \theta^{ltv} \tag{14}$$

is the marginal collateral value of housing, defined as the benefit to the borrower of the relaxation in her overall constraint obtained from an additional dollar of housing. The three terms in (14) represent the path through which additional collateral provides value to the borrower through a relaxed credit limit. Starting from the right, θ^{ltv} determines how much an additional dollar of housing collateral relaxes a borrower's LTV limit. The next term, $F^{ltv}_t = 1 - \Gamma_e(\bar{e}_t)$ is the fraction of borrowers constrained by LTV. Since only these borrowers face binding LTV limits, this term reflects the effect of relaxing LTV limits on the *overall* population limit $\bar{m}_t$. Finally, the term μ_t represents the value to the borrower of having the overall limit relaxed.

Given this definition, the denominator of (13) represents the collateral premium for housing: when an additional unit of housing is more valuable to the borrower as collateral, the borrower is willing to pay more for a unit of housing. But because debt cannot be costlessly collateralized every period, a negative collateral value term $\mathcal{C}_{t+1}$ also appears in the numerator. This is due to the fact that p^h_t is the price of a house that can be immediately used to collateralize a new loan, and therefore has full collateral value. But with probability $1 - \rho_{t+1}$, a given borrower will not obtain a new loan next period. In these states of the world, the borrower does not receive the collateral benefit of housing, which must therefore be subtracted off.[30]

Finally, from the borrower's choice of ρ_t, the fraction of loans to prepay, we obtain

[30] For intuition, $(1 - \mathcal{C}_t)p^h_t$ is the price that borrowers would be willing to pay for an additional unit of housing in cash (e.g., with no mortgage).

the optimal ratio

$$\rho_t = \Gamma_\kappa \left(\underbrace{(1 - \Omega^m_{b,t}) \left(1 - \frac{(1-\nu)\pi_t^{-1} m_{t-1}}{m_t^*}\right)}_{\text{new debt}} - \underbrace{\Omega^x_{b,t} \left(q_t^* - \bar{q}_{t-1} \frac{(1-\nu)\pi_t^{-1} m_{t-1}}{m_t^*} \right)}_{\text{new payments}} \right). \tag{15}$$

The term inside the c.d.f. Γ_κ represents the marginal benefit to prepaying an additional unit of debt. This can be decomposed into three terms. First, the term labeled "new debt" represents the borrower's gain from obtaining new face value debt. The benefit to an additional unit of debt, measured in dollars, is unity (the amount received from the saver), whereas the cost is Ω^m. Multiplying the net gain $(1 - \Omega^m)$ by the quantity of new debt yields the total gain to the borrower. The second term, labeled "new payments" represents the effect on the borrower of changing her promised payments. This change occurs both because the quantity of debt is changing, but also because the interest rate on the entire existing stock of debt is altered by prepayment.

4.2 Saver Optimality

The saver optimality conditions similar to those of the borrower, and are defined by

$$\begin{aligned} w_t &= -\frac{u^n_{s,t}}{u^c_{s,t}} \\ 1 &= R_t \mathbb{E}_t \left[\Lambda_{s,t+1} \pi_{t+1}^{-1} \right] \\ 1 &= \Omega^m_{s,t} + \Omega^x_{s,t} q_t^*. \end{aligned}$$

where $\Omega^m_{s,t}$ and $\Omega^x_{s,t}$ are the marginal continuation *benefits* to the saver of an additional unit of face value and an additional dollar of promised initial payments, respectively. These values are defined by

$$\Omega^m_{s,t} = \mathbb{E}_t \left\{ \Lambda_{s,t+1} \pi_{t+1}^{-1} \left[(1-\nu)\rho_t + (1-\nu)(1-\rho_{t+1}) \Omega^m_{s,t+1} \right] \right\} \tag{16}$$

$$\Omega^x_{s,t} = \mathbb{E}_t \left\{ \Lambda_{s,t+1} \pi_{t+1}^{-1} \left[1 + (1-\nu)(1-\rho_{t+1}) \Omega^x_{s,t+1} \right] \right\}. \tag{17}$$

These expressions are generally identical to the equivalent terms with the borrower's problem, with the exception that savers are unconstrained ($\mu = 0$), use a different stochastic discount factor, do not optimize over housing, and have an additional optimality condition from trade in the one-period bond.

4.3 Intermediate and Final Good Producer Optimality

The solution to the intermediate and final goods producers' problems is standard and can be summarized by the following system of equations

$$
\begin{aligned}
\mathcal{N}_t &= y_t \left(\frac{mc_t}{mc^{ss}}\right) + \zeta \mathbb{E}_t \left[\Lambda_{s,t+1} \left(\frac{\pi_{t+1}}{\pi^{ss}}\right)^{\lambda} \mathcal{N}_{t+1}\right] \\
\mathcal{D}_t &= y_t + \zeta \mathbb{E}_t \left[\Lambda_{s,t+1} \left(\frac{\pi_{t+1}}{\pi^{ss}}\right)^{\lambda-1} \mathcal{D}_{t+1}\right] \\
\tilde{p}_t &= \frac{\mathcal{N}_t}{\mathcal{D}_t} \\
\pi_t &= \pi^{ss} \left[\frac{1-(1-\zeta)\tilde{p}_t^{1-\lambda}}{\zeta}\right]^{\frac{1}{\lambda-1}} \\
\Delta_t &= (1-\zeta)\tilde{p}_t^{-\lambda} + \zeta(\pi_t/\pi^{ss})^{\lambda}\Delta_{t-1} \\
y_t &= \frac{a_t n_t}{\Delta_t}
\end{aligned}
$$

where y_t is total output, $\mathcal{N}_t$ and $\mathcal{D}_t$ are auxiliary variables, $\tilde{p}_t$ is the ratio of the optimal price for resetting firms relative to the average price, and Δ_t is price dispersion.

4.4 Calibration

The calibrated parameter values are detailed in Table 1. While many parameters can be set to standard values, given the wealth of previous work on New Keynesian DSGE models, several parameters relate to features that are new to the literature, and are calibrated to several sets of microdata.

The first such calibration is for the income heterogeneity of the borrowers, Γ_e. I parameterize this distribution so that $e_{i,t}$ is log-normal, with $\log e_{i,t} \sim N\left(-\sigma_e^2/2, \sigma_e^2\right)$. In this case, the properties of the lognormal distribution imply the closed form expression

$$
\int^{\bar{e}_t} e_i \, d\Gamma_e(e_i) = \Phi\left(\frac{\log \bar{e}_t - \sigma_e^2/2}{\sigma_e}\right)
$$

which is required for computing (6) and (9). Therefore, calibrating this distribution requires only choosing the parameter σ_e. In reality, unlike in the model, borrowers may differ both in their incomes and in the size of the house that they purchase, so choose to this parameter to match the standard deviation of $\log(h_{i,t}/y_{i,t})$ ratios for new borrowers, obtained using loan-level data from Fannie Mae, averaged over all quarters from 2000 to 2014. [31]

[31] Results using loan-level data from Freddie Mac were nearly identical.

Table 1: Parameter Values: Baseline Calibration

Parameter	Name	Value	Internal	Target/Source
Demographics and Preferences:				
Fraction of borrowers	χ_b	0.35	N	2001 SCF (see text)
Income dispersion	σ_e	0.411	N	Fannie Mae microdata (see text)
Borr. discount factor	β_b	0.95	N	Standard
Saver discount factor	β_s	0.993	Y	Real rate = 3%
Borr. housing preference	ξ	0.299	Y	$h_b/w_b n_b = 8.68$ (2001 SCF)
Disutility of labor scale	η	7.958	Y	$n = 1/3$
Inv. Frisch elasticity	φ	1.0	N	Standard
Housing and Mortgages:				
Mortgage amortization	ν	1/120	N	30-year duration
Max PTI ratio	θ^{pti}	0.36	N	See text
Max LTV ratio	θ^{ltv}	0.85	N	See text
Issuance cost mean	μ_κ	0.188	Y	Average prepayment rate
Issuance cost scale	s_κ	0.033	Y	See text
PTI offset (taxes, etc.)	τ	0.005	Y	$q^* + \tau = 10.6\%$ (annual)
PTI offset (other debt)	ω	0.08	N	See text
Log housing stock	$\log \bar{H}$	2.090	Y	$p^h = 1$ in steady state
Log saver housing stock	$\log \bar{H}_s$	2.082	Y	Saver demand correct in steady state
Productive Technology:				
TFP (mean)	μ_a	1.099	Y	$y_t = 1$ in steady state
TFP (pers.)	ϕ_a	0.9641	N	Garriga et al. (2015)
TFP (std.)	σ_a	0.0082	N	Garriga et al. (2015)
Variety elasticity	λ	6.0	N	Standard
Price stickiness	ζ	0.75	N	Standard
Monetary Policy:				
Steady state inflation	π^{ss}	1.0075	N	3% annual inflation in steady state
Taylor rule (inflation)	ψ_π	1.5	N	Standard
Taylor rule (smoothing)	ϕ_r	0.89	N	Campbell, Pflueger, and Viceira (2014)
Trend infl (pers.)	$\phi_{\bar{\pi}}$	0.994	N	Garriga et al. (2015)
Trend infl (std.)	$\sigma_{\bar{\pi}}$	0.0015	N	Garriga et al. (2015)

I calibrate the fraction of borrowers χ_b and the housing preference parameter ξ to match moments from the 2001 Survey of Consumer Finances. First, I separate out households with more than one month's liquid assets (45.4% of the sample) who I associate with savers in the model.[32] Of the remaining households (with low liquid balances), I identify those with both a house and a mortgage (24.3% of the sample), and associate them with the borrowers in the model, a categorization closely related to the "wealthy hand-to-mouth" agents of Kaplan and Violante (2014) and Kaplan et al. (2014).[33] The remaining 30.4% of households have low liquid balances but do not hold a mortgage, and are mostly renters.[34] Since this population does not fit well into either category, I exclude them for purposes of calibration and normalize the other two groups to the value $\chi_b = 0.35$.

Next, I calibrate the prepayment cost distribution to match Fannie Mae MBS prepayment data. The first step is to choose a functional form for Γ_κ. In the data, the fraction of loans prepaid at quarterly frequency varies from 1.0% to 20.8%, despite a wide range of interest rate and housing market conditions. As a result, a better fit is attained by choosing Γ_κ to be a mixture, such that with 1/4 probability, κ is drawn from a logistic distribution, and with 3/4 probability, $\kappa = \infty$, in which case borrowers never prepay, so that[35]

$$\Gamma_\kappa(\kappa) = \frac{1}{4} \cdot \frac{1}{1 + \exp\left(-\frac{\kappa - \mu_\kappa}{s_\kappa}\right)}.$$

This functional form is parameterized by a location parameter μ_κ and a scale parameter s_κ For a given value of s_κ, the parameter μ_κ is chosen to match the mean prepayment rate on fixed rate mortgages over the sample 1994-2015 (source: eMBS).

For the parameter s_κ, I run a prepayment regression

$$\text{logit}(cpr_{i,t}) = \gamma_{0,t} + \gamma_1(q_t^* - \bar{q}_{i,t-1}) + e_{i,t} \tag{18}$$

[32]Although 51.4% of "saver" households hold a mortgage in the data, I still categorize them as savers as they do not appear to be liquidity constrained, and therefore should not be sensitive to changes in their debt limits or transitory changes to income. In the model, savers can trade mortgages (and any other financial contract) within the saver family. Classifying all mortgage holders as borrowers would increase the value of χ_b and likely strengthen the impact of the mortgage credit channel.

[33]Households without liquid assets but with home equity lines of credit (HELOCs) may not be credit constrained, despite low liquid balances. Excluding these households would yield a very similar borrower fraction of 21.8% before normalization.

[34]75.4% of these households do not own houses.

[35]This assumption implies that $4 \cdot \rho$, which is approximately the annualized prepayment rate, will have a logistic form that matches well with the reduced-form prepayment literature. This mixture distribution can be motivated by inertial behavior or inattention. However, the model can also be calibrated without the mixture distribution, with similar results.

using monthly MBS data from 1994-2015 with a wide range of coupon bins at each point in time,[36] where i varies across coupon bins, $cpr_{i,t}$ is the annualized prepayment rate, q_t^* is the weighted average coupon rate on newly issued MBS, and $\bar{q}_{i,t-1}$ is the weighted average coupon rate on loans in the bin at the start of the period.[37] By incorporating the time dummies $\gamma_{0,t}$ I am able to control for variation in aggregate economic conditions, so that γ_1 is identified only from cross-sectional variation in existing coupon rates within the same period. Applying the logistic assumption for Γ_κ and rearranging (15) yields

$$\text{logit}(\widetilde{cpr}_t) = \gamma_{0,t} - \frac{\Omega_{b,t}^x}{s_\kappa}\left(q_t^* - \bar{q}_{t-1}\frac{(1-\nu)\pi_t^{-1}m_{t-1}}{m_t^*}\right) \tag{19}$$

where $\widetilde{cpr}_t = 4\rho_t$ is the approximate annualized prepayment rate, and where here $\gamma_{0,t}$ captures all terms not depending on q_t^* or $\bar{q}_{t-1}$.[38] Given the near symmetry between (18) and (19), I calibrate s_κ so that in the steady state we have $\Omega_b^x/s_\kappa = \hat{\gamma}_1$, matching the sensitivities of prepayment to interest rate incentives in the model and in the regression. This procedure yields the values $s_\kappa = 0.033$ and $\mu_\kappa = 0.188$.[39]

For the LTV limit, $\theta^{ltv} = 0.85$ is close to the mean LTV at origination over the sample, and is chosen as a compromise between the mass constrained at 80%, and the masses constrained at higher institutional limits like 90% and 95%. For the PTI limit, I choose $\theta^{pti} = 0.36$ to match the pre-boom standard. It is worth noting, however, that since the bust, the main constraint on new loans appears to be not 36% but 45%, and going forward, the relevant ratio is likely to be the Dodd-Frank limit of 43%. Results using this value are similar, and can be found in the appendix.

I calibrate the offset term τ in the PTI constraint, so that $q_t^* + \tau$ is equal to 10.6% at an annualized rate, which is the interest and principal payment on a loan with a 8% interest rate (typical in the mid-1990s) under the exact amortization scheme for a FRM, plus 1.75% annually for taxes and insurance. Since the simpler geometrically-decaying coupon bonds in the model apply too much principal repayment at the start of the loan, this calibration makes sure that the initial payments are not unrealistically large for the

[36]Cross-sectional variation is obtained in the form of 35 different coupon bins ranging from 2% to 17%. These bins correspond roughly, but not exactly, to the coupon rate on the loan. See Fuster, Goodman, Lucca, Madar, Molloy, and Willen (2013) for an excellent description of how MBS coupon bins are constructed.

[37]The full results are reported in Table A.1 in the appendix.

[38]The exact rate would be $cpr_t = 1 - (1-\rho_t)^4$.

[39]These parameters imply high costs: the threshold borrower pays 13.1% in costs in the steady state, and the average cost among prepaying borrowers is 8.1%. These values greatly exceed standard closing costs on a new loan, in line with empirical evidence that borrowers often do not prepay even when financially advantageous (see e.g., Andersen, Campbell, Nielsen, and Ramadorai (2014), Keys, Pope, and Pope (2014)).

purpose of setting the PTI limit. I calibrate $\omega = 0.08$ to match the difference between the standard PTI limits when other debt is included (0.36) and is not included (0.28).

For the remaining parameters, I set $\beta_s = 0.993$ and $\pi^{ss} = 1.0075$ so that steady state real rates and inflation rates are each 3%. I set the borrower discount factor to 0.95, and calibrate the housing preference parameter ξ to 0.299, so that the steady state ratio of borrower house value to income $p_t^h h_{b,t}/w_t n_{b,t}$ matches the corresponding moment from the 2001 SCF of (8.68). To calibrate the exogenous processes for technology a_t and the inflation target $\bar{\pi}_t$, I follow Garriga et al. (2015), who also study the impact of these shocks on long-term mortgage rates. Finally, I calibrate the housing stock and saver housing demand so that the price of housing is unity in the steady state, and so the savers housing demand is equivalent to the amount they would demand in steady state if they were allowed to freely choose their housing allocation.[40]

5 Results: Interest Rate Transmission

This section uses numerical results to illustrate how the novel features of the model amplify transmission from nominal interest rates into debt, house prices, and economic activity, and the implications for monetary policy. The quantitative results in this section are obtained by linearizing the model around the deterministic steady state and calculating impulse responses to the model's fundamental shocks.

5.1 The Constraint Switching Effect

The first main innovation of the paper is to incorporate a PTI limit alongside a standard LTV limit, which profoundly influences the dynamics of debt and house prices in the model. To isolate the effects of this credit limit structure, I consider three alternative economies, which differ in their debt limits:

1. The *PTI Economy*: $\bar{m}_t = \bar{m}_t^{pti}$.
2. The *LTV Economy*: $\bar{m}_t = \bar{m}_t^{ltv}$.
3. The *Benchmark Economy*: $\bar{m}_t$ is defined as in (6).

[40]The saver's implied optimality condition for housing is

$$p_t^h = u_{s,t}^h/u_{s,t}^c + (1-\delta)\mathbb{E}_t\left[\Lambda_{s,t+1}p_{t+1}^h\right].$$

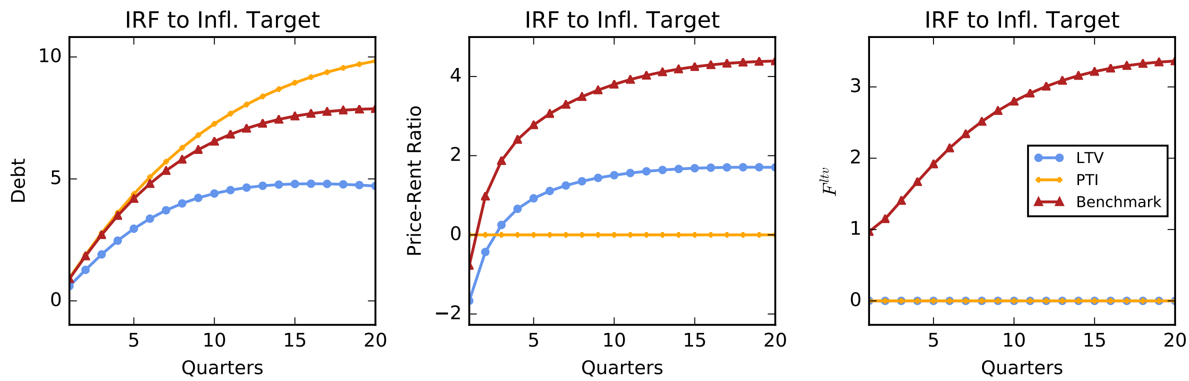


Figure 3: Impulse Response to -1% (Annualized) Inflation Target Shock: Comparison of LTV, PTI, Benchmark Economies

Note: A value of 1 represents a 1% increase relative to steady state, except for F^{ltv}, which is measured in percentage points.

These economies are otherwise identical in their specification and calibration, with the exception that the credit limit parameters θ^{ltv} and θ^{pti} are recalibrated in the PTI and LTV Economies to match the steady state debt limit in the Benchmark Economy.[41]

Figure 3 displays the response to a near-permanent -1% shock to the policy rule (inflation target), to demonstrate the dynamics of a persistent drop in nominal interest rates.[42] First, note that the PTI Economy displays a large debt response, with more than twice the increase after 20Q relative to the LTV Economy (9.8% vs. 4.7%). This occurs because PTI limits are themselves highly sensitive to interest rates with directly enter the constraint, with an elasticity of around 8 at steady state.[43]

Turning to the Benchmark Economy, we observe a substantial increase in debt and debt limits following the shock, following a path closer to that of the PTI Economy than that of the LTV Economy. This may be somewhat surprising, since in the model, as is typically found in the empirical literature, a majority of borrowers are constrained by LTV (75% in steady state).[44] As a result, while the minority borrowers limited by PTI will have their constraints greatly expanded in the Benchmark Economy, this by itself would not be sufficient to deliver the large aggregate response.

Instead, the key to this result lies in the interaction between the two constraints.

[41]The required values are $\theta^{ltv} = 0.710$ and $\theta^{pti} = 0.180$, respectively.

[42]In fact, this is a drop in nominal rates only, while real rates rise slightly.

[43]To understand this sensitivity, it may be helpful to consider a loan on which a borrower makes only interest payments. In this case a fall in the interest rate from 5% to 4%, would actually cut the borrower's interest payments by 20%, therefore allowing the borrower to obtain a 20% larger loan subject to her PTI limit. Accounting for payments of principal, taxes, insurance, etc., reduces the elasticity to ∼8%.

[44]The classic study is Linneman and Wachter (1989).

This occurs through movements in $\mathcal{C}_t$, the collateral value of housing, which is in turn driven by changes in F_t^{ltv}, the fraction of borrowers constrained by LTV. Intuitively, when borrowers are constrained by LTV, they are willing to pay a premium for housing, since it can be used as collateral to relax their borrowing limits. In contrast, when borrowers are limited by PTI, they receive no collateral benefit from housing, and are unwilling to pay this premium. When interest rates fall, as in Figure 3, PTI limits loosen. This increases the fraction of borrowers constrained by LTV, which in turn pushes up housing demand and house prices, as more borrowers are willing to pay a collateral premium for housing.

I call this channel — through which changes in the binding constraint for borrowers induce movements in house prices — the *constraint switching effect*. This effect provides a novel mechanism through which movements in interest rates can transmit into house prices, which requires the presence of both constraints, and is not present in a model with either constraint in isolation. As a result, the price-rent ratio rises by 4% in the Benchmark Economy, far more than in either the LTV or PTI Economies, where these interaction effects are absent.[45] This movement on house prices in turn amplifies the transmission into debt limits and credit growth in the Benchmark Economy. Because house prices have increased, even borrowers who were previously constrained by LTV — the majority of the population — find their borrowing limits relaxed, leading to a much larger increase in overall credit growth observed.[46]

5.2 The Frontloading Effect

While the presence of both LTV and PTI limits are sufficient to generate transmission into debt and house prices, it turns out that endogenous prepayment by borrowers is crucial for transmission into output and inflation. In this class of New Keynesian model, an increase in spending fueled by new credit can increase output, but only if it occurs in the short run, before most intermediate firms have an opportunity to reset their prices. While a fall in rates would raise debt *limits* immediately, if borrowers always prepaid at the average rate — with 4.5% of borrowers prepaying each quarter — most new credit issuance and spending would occur too far in the future to influence output. But when

[45] The moderate rise in price-rent ratios in the LTV Economy occurs for two reasons: first, because lower inflation slows effective amortization, and second, because impatient borrowers prefer the payment schedule in low-inflation environments, since lower expected inflation actually means more backloaded real payments. As a result, a fall in inflation expectations raises the shadow value of debt μ_t, and therefore collateral value.

[46] These effects can be separated by comparison to an alternative model in which the fraction F_t^{ltv} is fixed at its steady state level. Figure A.4 in the appendix compares these economies to show that without spillovers into house prices, the Benchmark Economy would look much more like the LTV economy, with weaker transmission of interest rates.

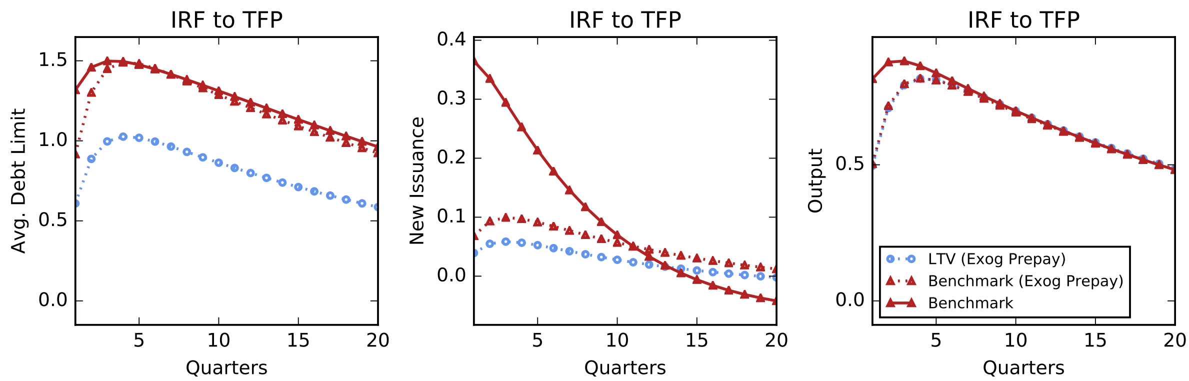


Figure 4: Impulse Response to 1% Technology Shock: Comparison of LTV (Exogenous Prepayment), Benchmark (Exogenous Prepayment), and Benchmark (Endogenous Prepayment) Economies

Note: A value of 1 represents a 1% increase relative to steady state, except for "New Issuance," $\rho_t(m_t^* - (1-\nu)\pi_t^{-1} m_{t-1})$, which is measured as a fraction of steady state output.

borrowers can choose when to prepay, a fall in rates will induce a wave of new issuance, as many borrowers choose to both lock in lower fixed rates, and also to take advantage of their newly higher credit limits. The result is a large increase in spending on impact, and a much stronger effect on output, which I call the *frontloading effect*.

To see this mechanism in action, we can once again compare alternative economies to isolate a particular mechanism: the standard Benchmark Economy with endogenous prepayment determined by (15), and alternative versions of the LTV and Benchmark Economies with exogenous prepayment ($\rho_t = \bar{\rho}$). For a quantitative experiment, we can turn to Figure 4, which displays the response to a 1% technology shock. This shock puts downward pressure on inflation, leading to a fall in nominal rates.[47] Due to the constraint switching effect, this fall in rates leads to a large increase in debt limits in both Benchmark economies relative to the LTV Economy, of similar magnitude for both the endogenous and exogenous prepayment versions. But despite a similar rise in credit limits, the actual paths of credit issuance are very different in the exogenous and endogneous prepayment economies. While both exogenous prepayment economies exhibit a slow but steady stream of new issuance, the endogenous prepayment Benchmark Economy delivers sharply higher issuance of credit in the short run, which eventually falls below its exogenous prepayment counterparts.

As a result, we can see that despite the much greater loosening of credit limits in the Benchmark Economy, under exogenous prepayment the effects on output are virtually

[47] As with the inflation target shock, only nominal rates fall, as real rates rise.

identical to those of the LTV Economy, with the responses indistinguishable in Figure 4. But due to the frontloading effect, the output response on impact in the endogenous prepayment Benchmark Economy is 0.26% more than in either of the exogenous prepayment, an increase of 52%. These results indicate that the prepayment behavior of borrowers may be of primary importance for understanding the output response to movements in interest rates.

5.3 Monetary Policy

The influence of the constraint switching and frontloading effects on interest rate transmission have important implications for monetary policy. While I have been assuming until now that the central bank follows the policy rule (7), the central bank is capable of perfectly stabilizing inflation in this model. While not as empirically realistic as (7), this type of interest rate rule is useful for evaluating the effectiveness of monetary policy, since it provides a natural benchmark for its effectiveness: how much the policy rate must move in order to exactly return inflation to target following a shock. To characterize this policy formally, we can take the limit of (7) as $\psi_\pi \to \infty$, to obtain the alternative monetary policy equation (8), where the policy rate R_t must implicitly adjust so as to meet the inflation target.

The impulse response to a 1% technology shock under this rule is shown in Figure 5. To demonstrate the effect of the new features of this paper, the plot compares an LTV Economy with exogenous prepayment ($\rho_t = \bar{\rho}$) to a Benchmark Economy with endogenous prepayment. By construction, the shock causes no change in inflation due to the central bank's policy. Moreover, this policy eliminates the difference in the output response between the two models. However, the interest rate paths required to attain this stabilization are quite different, with the policy rate falling by much less — only 10% as much as under the LTV Economy on impact. Due to the effects of the mortgage credit channel, the fall in rates induces a much larger debt response in the Benchmark Economy relative to the LTV Economy, increasing borrower spending, and putting more upward pressure on prices. As a result, a smaller cut in rates is sufficient to return inflation to target.

From the above discussion, we can conclude that monetary policy is more effective at stabilizing inflation due to the mortgage credit channel. But, it is important to note that this increased effectiveness may not be without cost. As shown in Figure 5, smaller movements in the policy rate are made possible by much larger swings in debt levels. If policymakers are concerned with the stability of credit growth as well as of prices,

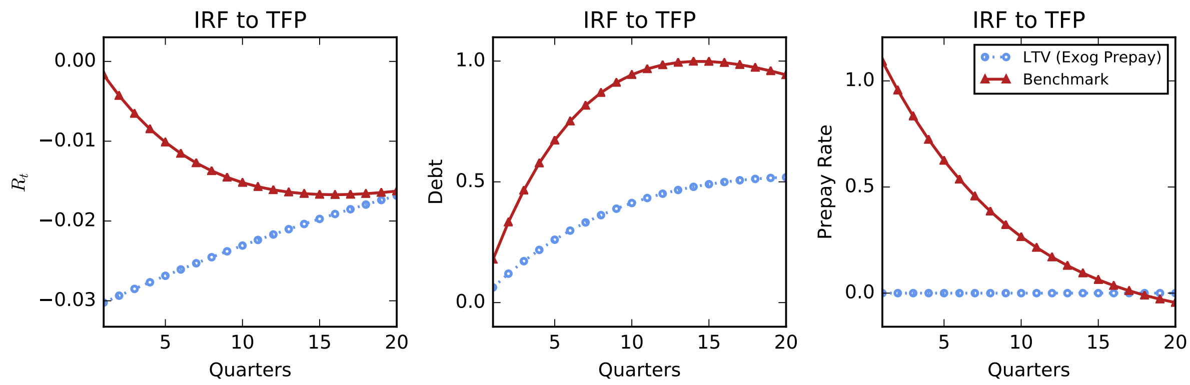


Figure 5: Impulse Response to 1% TFP Shock: Comparison of LTV (Exogenous Prepayment) and Benchmark (Exogenous Prepayment) Economies, Full Inflation Stabilization

Note: A value of 1 represents a 1% increase relative to steady state, except for "Prepay Rate," ρ_t, which is measured in percentage points at an annual rate.

then these dynamics may pose an important dilemma, as stabilizing prices may require *destabilizing* debt markets. For an important example, consider the position of the Federal Reserve in the early 2000s, which lowered the policy rate to low levels during a massive expansion of credit growth. Taylor (2007) has blamed this decision for the housing boom and bust that followed, while Bernanke (2010) has responded that the Federal Reserve's actions were appropriate given deflationary concerns. Ignoring the technical debate about whether or not the Federal Reserve adhered appropriately to a Taylor rule during this time, the preceding analysis shows that *both* arguments may have merit, in the sense that the actions taken by a central bank who stabilizes inflation perfectly may nonetheless exacerbate a credit boom. To the extent that policymakers wish to stabilize credit growth, this logic provides a rationale for imperfect inflation stabilization.

6 Results: Credit Standards and the Boom

In this section, I consider the implications of the model for the sources of the recent boom and bust, and for what type of macroprudential policy could limited its severity. I argue that changes in PTI standards, not LTV standards, provide the more compelling case for the source of the boom and bust, and that a cap on PTI ratios, not LTV ratios is the more effective macroprudential policy. To study these effects, in this section I compute a series of nonlinear transition paths. In each, I begin in the steady state, and then unexpectedly change the parameters of the model, starting the economy along a transition to the new steady state. After 32 quarters, I reverse the change in parameters, returning to the baseline, after which the economy begins transiting back toward the original steady state. To provide comparison to the data, I compare for each transition the path of implied price-rent ratios, given by $p_t^h/(u_{b,t}^h/u_{b,t}^c)$, and debt-to-household income ratios, given by m_t/y_t, and compare the observed change over the boom phase of the transition with the observed rises from 1997Q4 to 2006Q1, the period from the start of the boom to the peak in price-rent ratios.[48]

While I have been so far considering traditional macroeconomic shocks and their impacts through interest rates, let us now look at the the effects of changes in credit standards, which amounts to shifts in the values of θ^{ltv} and θ^{pti}. A large body of research has argued that a relaxation and tightening of credit standards was the primary driver of the boom and bust, and have typically focused on changes in LTV standards as the cause.

While these previous works have considered LTV limits alone, incorporating PTI limits allows me to answer two questions about the role of credit standards in the boom-bust. First, how does the existence of PTI limits alter the LTV relaxation story? Second, motivated by the empirical findings of Section 2.2, what is the impact of a relaxation of PTI standards themselves? To answer these questions, Figure 6 shows the results of two experiments in the Benchmark Economy. The first, labeled "LTV Liberalization," loosens LTV limits from 85% to 99%, and then unexpectedly restores them to 85% after 32 quarters. The second, labeled "PTI Liberalization," loosens PTI limits from 28% to 46%, and then unexpectedly restores them to 28% after 32 quarters.[49] These experiments produce strikingly different results. First, incorporating PTI limits severely dampens the impact of an LTV liberalization. Specifically, liberalizing LTV standards in the Benchmark Economy creates only a small rise in debt (19% of observed increase in debt-to-household-income) and actually causes house prices to *fall* (-2% of observed increase in price-rent ratios).[50]

The inability of a relaxation of LTV to produce a large boom in the presence of

[48] Source: Federal Reserve Board of Governors, Flow of Funds. Prices are taken as household real estate values (LM155035015.Q) while debt is taken as household home mortgages (FL153165105.Q). Household income is disposable personal income (FA156012005.Q).

[49] This choice of the liberalized PTI limit is motivated by evidence showing bunching of PTI ratios for non-agency loans at 50%. Since it is not clear whether this cap includes other debt payments (implying $\theta^{pti} = 0.5$) or does not include other debt payments ($\theta^{pti} \simeq 0.58$), I choose the intermediate value of $\theta^{pti} = 0.54$.

[50] In the LTV Economy version of the model (with only LTV limits), however, a large boom caused by LTV relaxation is possible, showing that the absence of a PTI limit is crucial for earlier findings that the boom was driven by a liberalization of LTV. Figure A.5 in the appendix shows the nonlinear transition path generated in the LTV Economy by unexpectedly relaxing LTV standards by ten percentage points, and then unexpectedly returning them to their initial value 32 quarters later, which generates a large increase in debt and price-rent ratios.

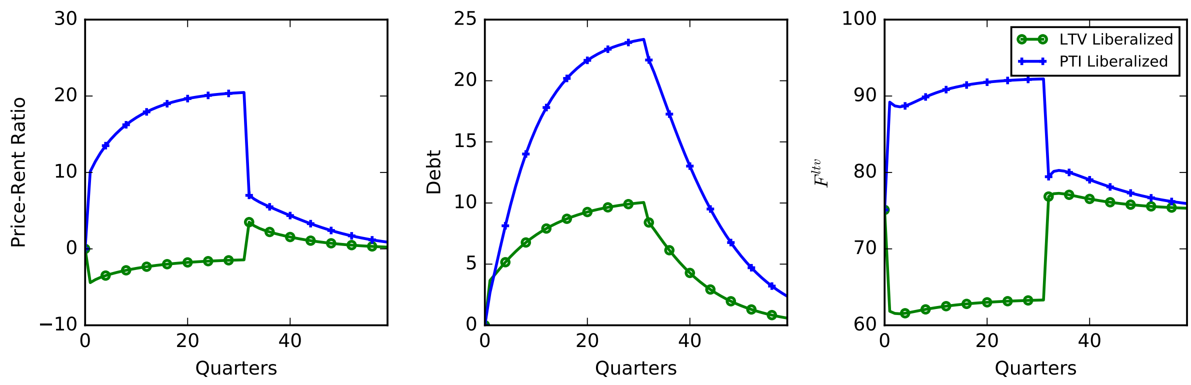


Figure 6: Credit Loosening Experiment: LTV Liberalization vs. PTI Liberalization

Note: A value of 1 represents a 1% increase relative to steady state, except for F^{ltv}, which is measured in percentage points.

PTI limits occurs for two reasons. First, there is a direct effect as borrowers hit their PTI constraints, limiting the increase in debt. But the addition of PTI limits also has important general equilibrium effects. As LTV standards are loosened, the share of borrowers constrained by LTV, F^{ltv}, falls by more than 10 percentage points. Due to the constraint switching effect, this puts substantial downward pressure on house prices and causes price-rent ratios to fall. This not only makes it difficult to generate a housing boom through LTV liberalization, but also dampens the rise in debt further, since LTV limits are no longer endogenously loosened due to a rise in house prices.

In contrast, the relaxation of PTI standards generates a large boom in debt and house prices, accounting for 38% of the increase price-rent ratios and 47% of the increase in debt-to-household-income ratios over the boom. These findings point to a liberalization of PTI limits as a key source of the boom-bust, potentially explaining up to half of the variation over the cycle. In this case, raising maximum PTI ratios causes more borrowers to be constrained by LTV, with F_t^{ltv} increasing by more than 10 percentage points on impact, and continuing to rise through the boom. Through the constraint switching effect, this pushes up house prices and price-rent ratios, which then endogenously loosens LTV limits, leading to large increases in house prices and debt, just as observed in the data. These results point to changes in PTI limits a key driver of the housing boom and bust.

While the experiments above only consider the possibility that credit standards were loosened for one constraint or the other, it is likely that both constraints saw a relaxation in credit standards. A path loosening $(\theta^{ltv}, \theta^{pti})$ from $(0.85, 0.36)$ to $(0.99, 0.54)$ and then unexpectedly returning them to their initial values after 32 quarters can be found in

Figure 7. This path generates a larger increase in debt (89%) of the observed increase in debt-to-household-income ratios) relative to the experiment relaxing PTI limits only, but explains roughly the same amount of the variation in house prices and price-rent ratios. As a result I conclude that looser LTV ratios may have played a limited role in the boom, but were only able to do so due to the contemporaneous liberalization of PTI limits.

These results are not only of historical interest for their insights about the sources of the boom-bust, but also matter for macroprudential policy. If boom-bust cycles can be caused or amplified by changes in credit standards, one potential policy response is to regulate credit standards, preventing them from loosening in the first place. Indeed, as documented by e.g., Jácome and Mitra (2015), regulatory caps on LTV and PTI ratios are common around the world, and are even manipulated by policymakers seeking to stabilize credit and housing markets. During and prior to the boom, the US had no legal limits on these ratios, which were imposed by mortgage underwriters, most influentially Fannie Mae and Freddie Mac. But perhaps the most important mortgage market reform of the Dodd-Frank Act was to impose a 43% cap on PTI ratios.[51]

Faced with this choice, the model clearly implies that indeed, a cap on PTI ratios, not LTV ratios, is the more effective macroprudential policy for limiting the amplitude of boom-bust cycles. A first piece of evidence follows immediately from the results above, which show that a fixed PTI limit can prevent a boom caused by the relaxation of LTV standards, but that an economy with a fixed LTV standard can still see a large boom if PTI standards are loosened. To demonstrate this quantitatively, I include an additional transition path, shown in Figure 7, in which LTV and PTI are both liberalized, but θ^{pti} is only allowed to rise to the Dodd-Frank limit of 43%. While not eliminating the boom and bust, this path shows that the Dodd-Frank limit would have substantially limited the boom, reducing the rise in credit growth, house prices, and price-rent ratios by more than half, and leading to a much smaller crash upon reversal.

Moreover, a cap on PTI ratios is also effective at limiting booms and busts caused by risk factors other than changes in credit standards, such as a change in housing preferences, or unrealistic house price expectations. As these forces push up house prices, many borrowers will again switch from being LTV-constrained to PTI-constrained, dampening the rise in debt and price-rent ratios, just as in the LTV liberalization example.[52] These

[51]Technically, this is not a hard limit on all mortgages, but a restriction on Qualified Mortgages, a class of mortgage that lenders are strongly incentivized to issue.

[52]For an example this phenomenon, I compute an additional transition path, shown in Figure A.6, that generates a boom and bust by first increasing the housing preference parameter, ξ, by 25%, and then unexpectedly returning it to its baseline value 32 quarters later. In the LTV Economy, this generates a large boom and bust, as rising house prices endogenously loosen LTV limits. But in the Benchmark

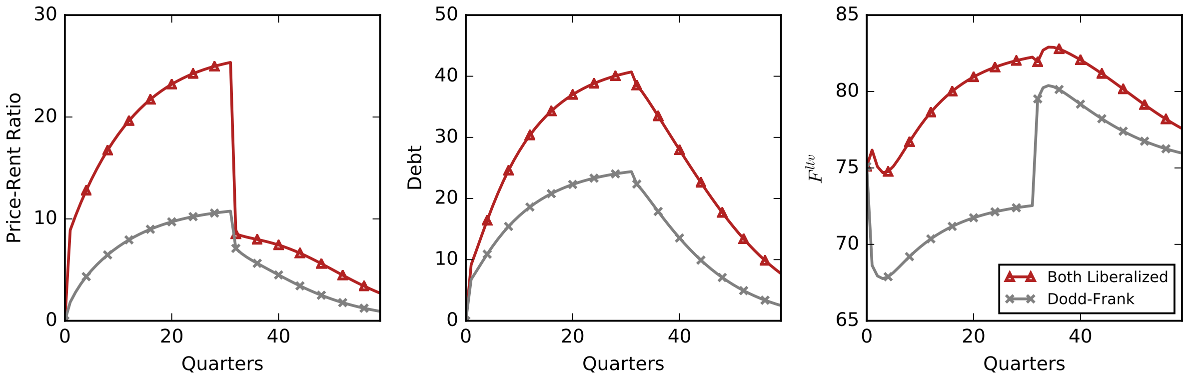


Figure 7: Credit Loosening Experiment: Full Liberalization vs. Approximate Dodd-Frank Limit

Note: A value of 1 represents a 1% increase relative to steady state, except for F^{ltv}, which is measured in percentage points.

results therefore indicate that while PTI liberalization is a sufficient condition for explaining only part of the boom, it was likely a *necessary* condition for these other important causes to have contributed as much as they did in generating the remainder of the boom.

7 Conclusion

In this paper, I developed a general equilibrium framework centered on two novel features: the combination of LTV and PTI limits, and the endogenous prepayment of long-term debt. When calibrated to US mortgage microdata, these features greatly amplify transmission from interest rates into debt, house prices, and economic activity. The effects on credit and house prices are created largely by the constraint switching effect, through which changes in which of the two constraints is binding for borrowers translate into movements in house prices, while the effects on economic activity are due mainly to the frontloading effect, through which the endogenous prepayment decisions of borrowers generate waves of new borrowing and spending following a movement in interest rates. Monetary policy is more effective at stabilizing inflation due to these forces, but contributes to larger movements in credit growth, posing a potential trade-off for policymakers. Finally, I argued that a PTI liberalization appears essential to explaining the boom-bust, and that a cap on PTI ratios, not LTV ratios, is the more effective macroprudential policy.

This work leaves a number of avenues open for future research. Perhaps most important, the framework abstracts from default: the primitive risk that limits on LTV and

Economy, PTI limits substantially limit the boom-bust cycle.

PTI are designed to mitigate. Incorporating default risk would allow for a much more comprehensive analysis of the costs and benefits of LTV, PTI, or alternative underwriting limits, aside from the effects on macroeconomic transmission highlighted here. A second important extension would be the addition of endogenous mortgage choice. Borrowers constrained by PTI have strong incentives to seek products with lower mortgage payments. In particular, this may have played a role in the enormous increase in the share of borrowers taking on adjustable-rate and interest-only mortgage products during the boom, with potentially important consequences for monetary policy and mortgage regulation.

References

Adelino, M., A. Schoar, and F. Severino (2015a): "Changes in Buyer Composition and the Expansion of Credit During the Boom," Tech. rep., National Bureau of Economic Research.

——— (2015b): "Loan Originations and Defaults in the Mortgage Crisis: Further Evidence," Tech. rep., National Bureau of Economic Research.

——— (2015c): "Loan Originations and Defaults in the Mortgage Crisis: The Role of the Middle Class," .

Aladangady, A. (2014): "Homeowner Balance Sheets and Monetary Policy," Tech. rep., FEDS Working Paper.

Andersen, S., J. Y. Campbell, K. M. Nielsen, and T. Ramadorai (2014): "Inattention and Inertia in Household Finance: Evidence From the Danish Mortgage Market," Unpublished Paper, Available at SSRN, No. 2463575.

Auclert, A. (2015): "Monetary Policy and the Redistribution Channel," Unpublished Paper, Massachusetts Institute of Technology.

Bernanke, B. S. (2010): "Monetary Policy and the Housing Bubble," in *Speech at the Annual Meeting of the American Economic Association, Atlanta, Georgia*, vol. 3.

Bhutta, N., H. Shan, and J. Dokko (2010): "The Depth of Negative Equity and Mortgage Default Decisions," FEDS Working Paper.

Calza, A., T. Monacelli, and L. Stracca (2013): "Housing Finance and Monetary Policy," *Journal of the European Economic Association*, 11, 101–122.

Campbell, J. R. and Z. Hercowitz (2005): "The Role of Collateralized Household Debt in Macroeconomic Stabilization," Tech. rep., National Bureau of Economic Research.

Campbell, J. Y. and J. F. Cocco (2015): "A Model of Mortgage Default," *The Journal of Finance*.

Campbell, J. Y., C. Pflueger, and L. M. Viceira (2014): "Monetary Policy Drivers of Bond and Equity Risks," Tech. rep., National Bureau of Economic Research.

Chatterjee, S. and B. Eyigungor (2015): "A Quantitative Analysis of the US Housing and Mortgage Markets and the Foreclosure Crisis," FRB of Philadelphia Working Paper.

Chen, H., M. Michaux, and N. Roussanov (2013): "Houses as ATMs? Mortgage Refinancing and Macroeconomic Uncertainty," Tech. rep., National Bureau of Economic Research.

Corbae, D. and E. Quintin (2013): "Leverage and the Foreclosure Crisis," Tech. rep., National Bureau of Economic Research.

Davis, M. A. and S. Van Nieuwerburgh (2014): "Housing, Finance and the Macroeconomy," Tech. rep., National Bureau of Economic Research.

Di Maggio, M. and A. Kermani (2015): "Credit-Induced Boom and Bust," Unpublished Paper, Haas School of Business, University of California, Berkeley.

Elenev, V., T. Landvoigt, and S. Van Nieuwerburgh (2015): "Phasing Out the GSEs," *Available at SSRN.*

Favara, G. and J. Imbs (2015): "Credit Supply and the Price of Housing," *The American Economic Review*, 105, 958–992.

Favilukis, J., D. Kohn, S. C. Ludvigson, and S. Van Nieuwerburgh (2012): "International Capital Flows and House Prices: Theory and Evidence," in *Housing and the Financial Crisis*, University of Chicago Press, 235–299.

Favilukis, J., S. C. Ludvigson, and S. Van Nieuwerburgh (2014): "Foreign Ownership of US Safe Assets: Good or Bad?" Tech. rep., National Bureau of Economic Research.

——— (2015): "The Macroeconomic Effects of Housing Wealth, Housing Finance, and Limited Risk-Sharing in General Equilibrium," *Journal of Political Economy, Forthcoming.*

Foote, C. L., K. Gerardi, and P. S. Willen (2008): "Negative Equity and Foreclosure: Theory and Evidence," *Journal of Urban Economics*, 64, 234–245.

Fuster, A., L. Goodman, D. O. Lucca, L. Madar, L. Molloy, and P. Willen (2013): "The Rising Gap Between Primary and Secondary Mortgage Rates," *Economic Policy Review*, 19.

Garriga, C., F. E. Kydland, and R. Sustek (2015): "Mortgages and Monetary Policy," Working Paper 19744, National Bureau of Economic Research.

Ghent, A. (2012): "Infrequent Housing Adjustment, Limited Participation, and Monetary Policy," *Journal of Money, Credit and Banking*, 44, 931–955.

Gorea, D. and V. Midrigan (2015): "Liquidity Constraints in the US Housing Market," Unpublished Paper, New York University.

Guler, B. (2014): "Innovations in Information Technology and the Mortgage Market," *Review of Economic Dynamics.*

Iacoviello, M. (2005): "House Prices, Borrowing Constraints, and Monetary Policy in the Business Cycle," *American economic review*, 739–764.

Iacoviello, M. and S. Neri (2010): "Housing Market Spillovers: Evidence From an Estimated DSGE Model," *American Economic Journal: Macroeconomics*, 2, 125–164.

Iacoviello, M. and M. Pavan (2013): "Housing and Debt Over the Life Cycle and Over the Business Cycle," *Journal of Monetary Economics*, 60, 221–238.

Jácome, L. I. and S. Mitra (2015): "LTV and DTI Limits–Going Granular," Tech. rep., IMF Working Paper.

Justiniano, A., G. E. Primiceri, and A. Tambalotti (2015): "Household Leveraging and Deleveraging," *Review of Economic Dynamics*, 18, 3–20.

Kaplan, G. and G. L. Violante (2014): "A Model of the Consumption Response to Fiscal Stimulus Payments," *Econometrica*, 82, 1199–1239.

Kaplan, G., G. L. Violante, and J. Weidner (2014): "The Wealthy Hand-To-Mouth," Tech. rep., National Bureau of Economic Research.

Kermani, A. (2012): "Cheap Credit, Collateral and the Boom-Bust Cycle," Unpublished Paper, Haas School of Business, University of California, Berkeley.

Keys, B. J., D. G. Pope, and J. C. Pope (2014): "Failure to Refinance," Tech. rep., National Bureau of Economic Research.

Khandani, A. E., A. W. Lo, and R. C. Merton (2013): "Systemic Risk and the Refinancing Ratchet Effect," *Journal of Financial Economics*, 108, 29–45.

Landvoigt, T. (2015): "Financial Intermediation, Credit Risk, and Credit Supply During the Housing Boom," Unpublished Paper, UT Austin, McCombs School of Business.

Laufer, S. (2013): "Equity Extraction and Mortgage Default," FEDS Working Paper.

Lee, D., C. J. Mayer, and J. Tracy (2012): "A New Look at Second Liens," Tech. rep., National Bureau of Economic Research.

Linneman, P. and S. Wachter (1989): "The Impacts of Borrowing Constraints on Homeownership," *Real Estate Economics*, 17, 389–402.

Liu, Z., P. Wang, and T. Zha (2013): "Land-Price Dynamics and Macroeconomic Fluctuations," *Econometrica*, 81, 1147–1184.

Mian, A. and A. Sufi (2008): "The Consequences of Mortgage Credit Expansion: Evidence From the 2007 Mortgage Default Crisis," Tech. rep., National Bureau of Economic Research.

——— (2014): "House Price Gains and US Household Spending From 2002 to 2006," Tech. rep., National Bureau of Economic Research.

Monacelli, T. (2008): "Optimal Monetary Policy With Collateralized Household Debt and Borrowing Constraints," in *Asset Prices and Monetary Policy*, University of Chicago Press, 103–146.

Pinto, E. J. (2011): "Government Housing Policies in the Lead-Up to the Financial Crisis: A Forensic Study," Unpublished Paper, American Enterprise Institute.

Rognlie, M., A. Shleifer, and A. Simsek (2014): "Investment Hangover and the Great Recession," Tech. rep., National Bureau of Economic Research.

Rubio, M. (2011): "Fixed-And Variable-Rate Mortgages, Business Cycles, and Monetary Policy," *Journal of Money, Credit and Banking*, 43, 657–688.

Smets, F. and R. Wouters (2007): "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," *The American Economic Review*, 97, 586–606.

Taylor, J. B. (2007): "Housing and Monetary Policy," Tech. rep., National Bureau of Economic Research.

A Appendix

A.1 Aggregation

This section demonstrates the equivalence of the representative borrower's problem with the individual borrower's problem. The proof of the equivalence of problems of the individual saver and representative saver is symmetric.

In the individual's problem I assume that each borrower owns a house of a given size but can freely buy and sell housing services on an intra-borrower rental market. The individual borrower's chooses consumption of nondurables $c_{i,t}$, rental of housing services $h_{i,t}^{rent}$, labor supply $n_{i,t}$, an indicator for the choice to prepay $\mathbb{I}_t \in \{0,1\}$, her target owned house size $h_{i,t}^*$ and mortgage size $m_{i,t}^*$ conditional on prepayment, and a vector of Arrow securities $a_{i,t}(s_{t+1})$ traded among borrowers to maximize (1) subject to the budget constraint

$$
\begin{aligned}
c_{i,t} \leq w_t n_{i,t} - \pi_t^{-1} x_{i,t-1} + \text{rent}_t(h_{i,t} - h_{i,t}^{rent}) - \delta p_t^h h_{i,t-1} \\
- \mathbb{I}_t(\kappa_{i,t}) \Big[\big(m_{i,t}^* - (1-\nu)\pi_t^{-1} m_{i,t-1} \big) - p_t^h \big(h_{i,t}^* - h_{i,t-1} \big) \\
- \left(\kappa_{i,t} - \text{Rebate}_t \right) m_{i,t}^* \Big] \\
+ a_{i,t-1}(s_t) + \sum_{s_{t+1}|s^t} p_t^a(s_{t+1}) a_{i,t}(s_{t+1})
\end{aligned}
\tag{20}
$$

the debt constraint

$$
m_{i,t}^* \leq \min(\bar{m}_{i,t}^{ltv}, \bar{m}_{i,t}^{pti}) \tag{21}
$$

and the laws of motion

$$
m_{i,t} = \mathbb{I}_t(\kappa_{i,t}) m_{i,t}^* + (1 - \mathbb{I}_t(\kappa_{i,t}))(1-\nu)\pi_t^{-1} m_{i,t-1} \tag{22}
$$

$$
h_{i,t} = \mathbb{I}_t(\kappa_{i,t}) h_{i,t}^* + (1 - \mathbb{I}_t(\kappa_{i,t})) h_{i,t-1} \tag{23}
$$

$$
x_{i,t} = \mathbb{I}_t(\kappa_{i,t}) q_t^* m_{i,t}^* + (1 - \mathbb{I}_t(\kappa_{i,t}))(1-\nu)\pi_t^{-1} x_{i,t-1}. \tag{24}
$$

The assumption that prepayment can be chosen only based on aggregate and not individual conditions, other than the draw of the transaction cost $\kappa_{i,t}$ is expressed by the lack of an i subscript on $\mathbb{I}_t$. This policy is chosen before time 0. The exact timing for the other controls is as follows:

1. Borrowers choose labor supply $n_{i,t}$.

2. Borrowers choose how much housing they will purchase if they choose to prepay.

3. Borrowers draw $\kappa_{i,t}$ and make their prepayment decisions based on the time 0 choice of $\mathbb{I}_t(\kappa_{i,t})$.

4. Borrowers draw $e_{i,t}$.

5. Borrowers choose their new loan size $m^*_{i,t}$ subject to their credit limit.

6. Borrowers realize insurance claims, buy new Arrow securities, and choose consumption and rental housing.

The Lagrangian is given by

$$
\begin{aligned}
\mathcal{L} = \sum_{t=0}^{\infty} \sum_{s^t} \beta_b^t \int_{e_i^t} \int_{\kappa_i^t} \int \int \Bigg\{ & u(c_{i,t}, h^{rent}_{i,t}, n_{i,t}) \\
& + \lambda_{i,t} \Bigg[w_t n_{i,t} - \pi_t^{-1} x_{i,t-1} + \text{rent}_t (h_{i,t} - h^{rent}_{i,t}) - \delta p^h_t h_{i,t-1} \\
& \quad - \mathbb{I}_t(\kappa_{i,t}) \Big(\big(m^*_{i,t} - (1-\nu)\pi_t^{-1} m_{i,t-1} \big) - p^h_t \big(h^*_{i,t} - h_{i,t-1} \big) \\
& \qquad - (\kappa_{i,t} - \text{Rebate}_t)\, m^*_{i,t} \Big) \\
& \quad + a_{i,t-1}(s_t) + \sum_{s_{t+1}|s^t} p^a_t(s_{t+1}) a_{i,t}(s_{t+1}) - c_{i,t} \\
& \quad + \mu_{i,t} \mathbb{I}_t(\kappa_{i,t}) \Big(\min(\bar{m}^{ltv}_{i,t}, \bar{m}^{pti}_{i,t}) - m^*_{i,t} \Big) \Bigg] \Bigg\} \, dF_e(e_i^t)\, dF_\kappa(\kappa_i^t)\, di.
\end{aligned}
$$

where superscript t implies the history from time 0 to t. The optimality conditions are

$$
\begin{aligned}
(c_{i,t}): \quad & u^c_{i,t} = \lambda_{i,t} \\
(a_{i,t}(s_{t+1})): \quad & p^a_t \lambda_{i,t} = \beta_b \mathbb{E}_t \lambda_{i,t+1} \\
(n_{i,t}): \quad & u^n_{i,t} + \lambda_{i,t} w_t \int e_{i,t}\, d\Gamma_e(e_{i,t}) \\
& \quad + \lambda_{i,t}\mu_{i,t} \int \int I_t(\kappa_{i,t}) \frac{\partial \bar{m}^{pti}_{i,t}}{\partial n_{i,t}} \mathbf{1}_{\{\bar{m}^{pti}_t < \bar{m}^{ltv}_t\}}\, d\Gamma_e(e_{i,t})\, d\Gamma_\kappa(\kappa_{i,t}) = 0 \\
(h^{rent}_{i,t}): \quad & u^h_{i,t} = \lambda_{i,t} \text{rent}_t \\
(h^*_{i,t}): \quad & \int \Big[\Omega^h_{i,t} - p^h_t + \mu_{i,t} \mathbf{1}_{\{e_{i,t} \geq \bar{e}_t\}} \theta^{ltv}_t p^h_t \Big]\, d\Gamma_e(e_{i,t}) = 0 \\
(m^*_{i,t}): \quad & \Omega^m_{i,t} + \Omega^x_{i,t} q^*_t - 1 + \mu_{i,t} = 0 \\
(\mathbb{I}_t(\kappa_{i,t})): \quad & \kappa^*_t = \int_{e_i^t} \int_{\kappa_i^{t-1}} \Big\{ (1 - \Omega^m_{i,t})(m^*_{i,t} - (1-\nu)\pi_t^{-1} m_{i,t-1}) \\
& \qquad - \Omega^x_{i,t}(q^*_t m^*_{i,t} - (1-\nu)\pi_t^{-1} x_{i,t-1})
\end{aligned}
$$

$$- (p^h_t - \Omega^h_{i,t})(h^*_{i,t} - h_{i,t-1})\Big\} \, dF(e^t_i) \, dF(\kappa^{t-1}_i)$$

where

$$\begin{aligned}
\Omega^h_{i,t} &= \mathbb{E}_t \left\{ \Lambda_{i,t+1} \Big[(\text{rent}_{t+1} - \delta) + \rho_{t+1} p^h_{t+1} + (1 - \rho_{t+1}) \Omega^h_{i,t+1} \Big] \right\} \\
\Omega^m_{i,t} &= \mathbb{E}_t \left\{ \Lambda_{i,t+1} \pi^{-1}_{t+1} \Big[(1 - \nu) \rho_{t+1} + (1 - \nu)(1 - \rho_{t+1}) \Omega^m_{i,t+1} \Big] \right\} \\
\Omega^x_{i,t} &= \mathbb{E}_t \left\{ \Lambda_{i,t+1} \pi^{-1}_{t+1} \Big[(1 - \nu) \rho_{t+1} + (1 - \nu)(1 - \rho_{t+1}) \Omega^m_{i,t+1} \Big] \right\}
\end{aligned}$$

and where $\Lambda_{i,t+1} = \beta \lambda_{i,t+1} / \lambda_{i,t}$. Note that the $\mathbb{I}(\kappa_{i,t})$ optimality condition comes from the threshold prepayer's indifference between prepaying and not prepaying. Moreover, by the assumption that the prepayment decision cannot condition on individual states, the probability of prepayment in the next period ρ_{t+1} does not depend on i or on other time t controls.

I now demonstrate that these optimality conditions are equivalent to those derived from the representative borrower's problem. I seek a symmetric equilibrium, in which all borrowers have equal lifetime wealth at time 0. From the $a_{i,t}(s_{t+1})$ optimality condition it follows that $\Lambda_{i,t+1}$ takes the identical value $\Lambda_{b,t+1}$ for all i. In the symmetric equilibrium, this implies that $\lambda_{i,t}$ are identical across all agents, and so $c_{i,t}$ is identically equal to $c_{b,t}/\chi_b$. As a result, immediately have $h^{rent}_{i,t}$ identically equal to $h_{b,t-1}/\chi_b$ across agents.

Therefore, all of the components of the Ω equations are identical. As a result, the $\Omega^h_{i,t}, \Omega^m_{i,t}, \Omega^x_{i,t}$ terms are identical across all agents i, and the Ω^m_t and Ω^x_t terms satisfy (11) and (12). Applying this result to the $m^*_{i,t}$ condition, we find that the value of $\mu_{i,t}$ is identical across borrowers, yielding (10). Substituting into the $h^*_{i,t}$ equation we obtain

$$\Omega^h_t = (1 - \mu_t F^{ltv}_t \theta^{ltv}_t) p^h_t$$

which combined with the Ω^h_t and $h^{rent}_{i,t}$ conditions yields (13). Substituting the result to date and applying the equilibrium condition $h^*_{i,t} = h_{i,t} = h_{b,t}$ yields (15). We can also integrate the $n_{i,t}$ condition over $e_{i,t}$ and $\kappa_{i,t}$ to yield

$$-\frac{u^n_{i,t}}{u^c_{i,t}} = w_t + \mu_t \rho_t \left(\frac{\theta^{pti}_t w_t}{q^*_t + \tau} \right) \int^{\bar{e}_t} e_i \, d\Gamma_e(e_{i,t})$$

which implies $n_{i,t} = n_{b,t}/\chi_b$ for all i, and delivers (9). Finally, integrating (22) - (24) yields (3) - (5).

A.2 Mortgage Underwriting

This section provides background on the origins and institutional details of the LTV and PTI constraints.

Although in the model I treat the LTV and PTI constraints facing borrowers as exogenous and institutional, the origin of these constraints lies with lenders' efforts to reduce credit risk. A lender takes a credit loss on a mortgage only if two events occur: the borrower defaults on the loan, and the value of the collateral is low enough that after foreclosure costs it is insufficient to pay off the balance on the loan. The purpose of LTV and PTI limits is to avoid this outcome. The *LTV ratio* on a loan is the ratio of the face value of the loan at origination to the value of the underlying housing collateral. By setting a cap on the LTV ratio, the lender reduces the probability that the property will not be worth enough to cover the balance on the loan in case of default. For example, a typical LTV limit of 80% allows the property to fall in value by up to 20% without becoming "underwater." Because borrowers can hold multiple liens on a single property, underwriters may instead consider the *combined LTV (CLTV) ratio*, which measures the total amount borrowed against the collateral as a fraction of the value of the house.

In contrast, PTI constraints are aimed at preventing the borrower from defaulting in the first place, by ensuring that she has sufficient income to cover her payments. Empirical evidence indicates that many borrowers appear to continue making payments even when their property is underwater, as long as their income allows them to do so, indicating a potentially important role for PTI limits in preventing credit losses.[53] The PTI ratio can be measured in one of two ways. The *front-end PTI ratio* on a loan is the ratio of all housing-related payments (principal, interest, taxes, and insurance) to the borrower's gross income. A typical maximum for the front-end ratio prior to the boom was 28%. However, similar to the logic behind computing a CLTV ratio, underwriters often compute a *back-end PTI ratio*, which is the ratio of *all* recurring debt payments to the borrower's gross income, including other mortgage products, auto loans, child support, etc. A typical maximum for the back-end ratio prior to the boom was 36%.

The Government Sponsored Enterprises (GSEs) Fannie Mae and Freddie Mac restrict the combinations of LTV and PTI ratios on loans that they insure.[54] The underwriting criteria set by the GSEs are generally thought of as the industry standard, and are often

[53] See e.g., Bhutta, Shan, and Dokko (2010), Foote, Gerardi, and Willen (2008).

[54] In practice, each GSE uses a proprietary algorithm to determine whether to accept a loan for securitization (*Desktop Underwriter* for Fannie Mae, *Loan Prospector* for Freddie Mac), so the actual standards cannot be perfectly known. However, a combination of GSE publications, including "manual underwriting guidelines" and analysis of origination data, gives a good idea of the true criteria.

emulated by banks issuing loans for their own portfolios. First, let us consider LTV limits.[55] In general, the GSEs will allow loans with high LTV ratios (e.g., 95% or 97%), but a key threshold occurs at 80%, after which the GSEs require that borrowers take out Private Mortgage Insurance (PMI) to cover the additional risk of default. The expense of this private insurance means that many borrowers are unwilling to go above 80%, with a large fraction of loans issued with exactly 80% LTV ratios as a result. In the theoretical analysis, I abstract from the ability to acquire PMI, but assume a LTV limit of 85% to match the mean LTV ratio on new loans, since many loans are issued at higher limits.

In contrast, PTI ratios are typically imposed as a hard cap, with no way to pay a premium to allow for a higher limit. For example, Fannie Mae's manual underwriting guidelines state that borrowers face one of two limits (36% or 45%) for PTI, depending on their LTV, credit score, and cash reserves. Fannie Mae and Freddie Mac both limit the back-end ratio when underwriting loans, and regulation in the Dodd-Frank reforms similarly targets the back-end ratio, making it the more important measure in practice. However, since I do not have other forms of recurring debt payments aside from mortgages, I impose front-end PTI limits in the model, and calibrate them accordingly.

A.3 Data Description

The analysis relies on three data sets, which are described below.

A.3.1 Pool-Level Agency MBS Data

This data set from eMBS[56] contains pool-level MBS data on all Fannie Mae, Freddie Mac, and Ginnie Mae products. The data is available at monthly frequency and is disaggregated by product type (e.g., 30-Year Fixed Rate), by coupon bin (in increments of 0.25% or 0.5%), and by either production year or state. Available variables include principal balance, conditional prepayment rate, level of issuance, weighted average coupon, and weighted average time to maturity.[57] The sample spans from Jan 1994 to Feb 2015.

[55] The GSEs generally focus on LTV ratios, not CLTV ratios for the first lien, because the first lien is senior to any other mortgages on the property.

[56] http://www.embs.com

[57] Issuance is not available at the state level, although it can be approximated given change in balance, prepayment, and average maturity.

A.3.2 Fannie Mae Loan-Level Data

This set is taken from Fannie Mae's Single Family Loan Performance Data.[58] From the Fannie Mae data description:

> The population includes a subset of Fannie Mae's 30-year, fully amortizing, full documentation, single-family, conventional fixed-rate mortgages. This dataset does not include data on adjustable-rate mortgage loans, balloon mortgage loans, interest-only mortgage loans, mortgage loans with prepayment penalties, government-insured mortgage loans, Home Affordable Refinance Program (HARP) mortgage loans, Refi Plus mortgage loans, and non-standard mortgage loans. Certain types of mortgage loans (e.g., mortgage loans with LTVs greater than 97 percent, Alt-A, other mortgage loans with reduced documentation and/or streamlined processing, and programs or variances that are ineligible today) have been excluded in order to make the dataset more reflective of current underwriting guidelines. Also excluded are mortgage loans originated prior to 1999, sold with lender recourse or subject to other third-party risk-sharing arrangements, or were acquired by Fannie Mae on a negotiated bulk basis.

The sample contains over 21 million loans acquired from Jan, 2000 to March 2012.

A.3.3 Freddie Mac Loan-Level Data

This set is taken from Freddie Mac's Single Family Loan-Level Dataset.[59] The data set contains approximately 17 million 30-year, fixed-rate mortgages originated between January 1, 1999, and September 30, 2013. Data plots corresponding to those for Fannie Mae data in the main text can be found in Figure A.3.

A.4 Extension: Adjustable-Rate Mortgages

This section considers a version of the model using adjustable-rate instead of fixed-rate mortgages. As in the FRM case, the saver gives the borrower \$1 at origination. In exchange, the saver receives $\$(1-\nu)^k q^*_{t+k-1}$ at time $t+k$, for all $k>0$ until prepayment, where $q^*_{t+k-1} = (R_{t+k-1}-1)+\nu$. This coupon rate is obtained from arbitrage considerations, since a saver must be indifferent between holding an adjustable-rate mortgage for one period and the one-period bond, since both are short-term risk-free assets.

Generally speaking, the main effect of moving from FRMs to ARMs on the equilibrium is that promised payment is no longer an endogenous state variable, but is instead defined

[58] http://www.fanniemae.com/portal/funding-the-market/data/loan-performance-data.html
[59] http://www.freddiemac.com/news/finance/sf_loanlevel_dataset.html

period-by-period using

$$x_t = q_t^* m_t.$$

Correspondingly, $\Omega^x_{j,t}$ and $\Omega^m_{j,t}$ can be combined into a single term $\Omega_{j,t}$, that represents the total effect of an additional unit of debt. As a result, the borrower's optimality conditions in the ARM case are now

$$\begin{aligned}\rho_t &= \Gamma_\kappa \left\{ (1-\Omega_{b,t}) \left(1 - \frac{(1-\nu)\pi_t^{-1} m_{t-1}}{m_t^*} \right) \right\} \\ \Omega_{b,t} &= 1 - \mu_t\end{aligned}$$

for

$$\Omega_{b,t} = \mathbb{E}_t \left\{ \Lambda^{\$}_{b,t+1} \Big[q_t^* + \nu\rho_{t+1} + \nu(1-\rho_{t+1})\Omega_{b,t+1} \Big] \right\}.$$

The saver's optimality conditions for m_t^* in the ARM case becomes

$$\Omega_{s,t} = 1$$

where

$$\Omega_{s,t} = \mathbb{E}_t \left\{ \Lambda^{\$}_{s,t+1} \left[q_t^* + (1-\nu)\rho_t + (1-\nu)(1-\rho_{t+1})\Omega_{s,t+1} \right] \right\}.$$

To see the impact of the type of mortgage contract on the dynamics, we can compare the Benchmark Economy with an ARM Economy in which contracts are defined as in this section. Impulse responses comparing the to an inflation target shock in the Benchmark (FRM) and ARM Economies can be seen in Figure A.7. As can be seen, the responses are qualitatively similar, but the Benchmark economy displays quantitatively larger responses of debt and output, due to the relatively higher increase in prepayments in the Benchmark Economy. The key idea is that a fall in long-term rates provides a larger incentive to prepay in the Benchmark Economy, where borrowers can lock in the low rate for the future, than in the ARM Economy, where interest rates are determined period-by-period, and the only motivation to prepay is to increase the debt balance.

A.5 Alternative PTI Calibration

In this section, I present results using a higher calibration for the PTI limit of 43%, corresponding to the maximum for Qualified Mortgages under the Dodd-Frank Act. Impulse responses, shown in Figure A.8, demonstrate strong effects of incorporating PTI limits alongside LTV limits, even though an even smaller minority of borrowers (13%) are constrained by PTI at equilibrium.

A.6 Credit and Redistribution

In this section, I relate to a recent line of work emphasizing the role of mortgages in the redistribution channel of transmission. The redistribution channel, documented extensively by Auclert (2015), but also crucial to the results of Rubio (2011) and Calza et al. (2013), amplifies movements in interest rates due to changes in real payments on the existing stock of debt. These papers demonstrate that, when borrowers have higher marginal propensities to consume than lenders, changes in real mortgage payments can transmit into economic activity by increasing demand. This can provide an important source of transmission in economies with adjustable-rate mortgages, where movements in short-term interest rates can cause substantial changes in real mortgage payments relative to an economy where mortgage payments are fully fixed.

While the main focus of my paper is on an entirely different channel — the mortgage credit channel — which works through changes in new credit issuance rather than changes in payments on existing credit, one novel feature of my framework is that it allows for redistribution even in fixed-rate mortgage economies. In contrast to the works listed above, in which fixed rate mortgage payments were assumed to be fully fixed and could not be changed, borrowers in my model can prepay their loans and replace them with new loans at new interest rates. These changes in interest rates on existing debt can lead to large transfers of present-value wealth between lenders and borrowers, usually in borrowers' favor. But despite these large transfers of wealth, I find that these redistributions have negligible aggregate effects in my model, due to the persistence of the transfers involved.

To understand the key intuition, assume that borrowers consume out of current income, while savers consume out of permanent income. A transfer of one dollar today from saver to borrower causes the borrower's income to rise by much more than the saver's permanent income falls, leading to an increase in total spending today. This is the force through which transitory changes in ARM payments create increases in total spending and demand. However, a *permanent* sequence of transfers changes the borrower's current income and saver's permanent income by the same amount, leading to perfectly offsetting consumption responses, and no change in net spending. When a fixed-rate mortgage is prepaid and replaced with a new loan at a different interest rate, the payments on the existing debt change by a constant amount for up to 30 years, changing borrower current income and saver income by nearly the same amount, and inducing only a small impact on aggregate spending.

To formalize these ideas, let us consider a simple partial equilibrium environment with a single borrower b and saver s. Each agent $j \in \{b, s\}$ has an exogenous income stream

$y_{j,t}$ and preferences over lifetime utility

$$V_{j,t} = \sum_{k=0}^{\infty} \beta_j^k \frac{c_{j,t+k}^{1-\gamma}}{1-\gamma}.$$

The saver has access to a storage technology with return R, and has discount factor $\beta_s = 1/R$. The borrower is credit constrained (hand-to-mouth) and consumes her resources in each period. It is straightforward to show that the equilibrium consumption plans are

$$\begin{aligned} c_{b,t} &= y_{b,t} \\ c_{s,t} &= (1 - R^{-1})W_s \end{aligned}$$

where present-value saver wealth is defined by

$$W_s \equiv \sum_{t=0}^{\infty} R^{-t} y_{s,t}.$$

From this benchmark, we can consider a sequence of transfers z_t from saver to borrower announced at $t = 0$. Let e.g., $dc_{b,t}$ denote the change in the consumption plan from before the announcement to after the announcement. Since

$$\begin{aligned} dc_{b,t} &= z_t \\ dc_{s,t} &= (1 - R^{-1})dW_s \\ dW_s &= -\sum_{t=0}^{\infty} R^{-t} z_t. \end{aligned}$$

the resulting impact on overall consumption is

$$dC_t \equiv dc_{b,t} + dc_{s,t} = z_t - (1 - R^{-1}) \sum_{k=0}^{\infty} R^{-k} z_t.$$

This setting can be used to consider the demand effects of both the redistribution channel and the credit channel. For a natural example of the redistribution channel's effects, we can consider $z_t = \phi_z^t z_0$, which could stand in for e.g., the effect of a persistent change in mortgage payments. In this case, algebra yields

$$dC_t = \left[\phi_z^t - \frac{R-1}{R-\phi_z} \right] z_0.$$

From this expression it is immediate that the effect on impact ($t = 0$) is decreasing in ϕ_z, and that as $\phi_z \to 1$ we have $dC_t \to 0$ for all t. By this logic, very persistent transfers can have their net impact cut substantially due to offsetting responses by the saver. In particular, for ϕ_z is set to 0.992, the persistence associated with the duration of a 30-year mortgage, the net impact is cut by nearly 60%. Note that since this experiment is performed in partial equilibrium, with no general equilibrium price adjustments or interest rate responses dampening effects, it implies that the effects of persistent redistribution due to changes in interest rates should be weak even at the zero lower bound.

To instead investigate demand effects through the credit channel, let us consider any sequence of transfers z_t with $\sum_{t=0}^{\infty} R^{-t} z_t = 0$. This type of transfer nests any sequence of credit issuance and repayment, since if D_t is the borrower stock of debt, we can define $z_t = dD_t - R \cdot dD_{t-1}$ to solve for the implied debt issuances dD_t. The key property of resource flows caused by credit issuance is that

$$dc_{s,t} = dW_s = 0$$

for all t. The intuition here is that since any credit arrangement occurs at market rates, the saver's wealth, and therefore permanent income, are not affected, so there is no impact on saver consumption — a result very similar to Ricardian equivalence. Since the borrower still consumes all her resources on hand in each period, the total impact on demand is $dC_t = z_t$, implying that net credit issuance passes one-for-one into aggregate demand.

In the full model, the dynamics of credit and redistribution are interlinked and difficult to disentangle. For example, changes in the interest rate on debt may redistribute, but may also change borrowers' decisions to prepay their loans and take on new credit, leading to consequences for credit growth. To distill the separate impacts of these channels, I instead consider a simpler environment with no endogenous debt dynamics, and directly impose the transfers discussed above. For credit growth, I assume

$$\tilde{m}_t = \phi_m \pi_t^{-1} \tilde{m}_{t-1} + \varepsilon_{\tilde{m},t}$$

and for a sequence of redistributive transfers, I assume the law of motion

$$z_t = \phi_z \pi_t^{-1} z_{t-1} + \varepsilon_{z,t}.$$

Total payments from borrower to lender are given by

$$\widetilde{x}_t = (R - \phi_m)\tilde{m}_t + z_t$$

where the tildes indicate that these laws of motion deviate from the benchmark model. I will refer to $\varepsilon_{\tilde{m},t}$ in this section as a credit issuance shock and $\varepsilon_{z,t}$ as a redistribution shock.

Impulse responses to these shocks, with $\phi_m = \phi_z = 0.992$, to match the duration of a 30-year mortgage, can be seen in Figure A.9. Although both shocks induce a substantial increase in borrower consumption, the aggregate impact on output of the credit issuance shock is much larger. As argued above, this is due to the fact that in response to a persistent redistribution, savers make a large offsetting change to their own consumption, which almost completely offsets the influence of the increase in borrower consumption. These results are not only of theoretical interest, but have implications for policy. For example, this analysis indicates that the Home Affordable Refinance Program (HARP), which allows underwater borrowers to refinance into mortgages with lower rates, but not to obtain new credit, are unlikely to have large demand effects through the MPC effects to which redistributive effects are traditionally ascribed, even at the zero lower bound.[60]

[60] The program could, however, deliver important effects by preventing default, regardless of its impact through the redistribution channel.

Appendix: Tables and Figures

Table A.1: Prepayment Regression

	CPR
$q_t^* - q_{i,t-1}$	0.7115
	(0.012)
Time FE	Yes
Observations	76,449
Adj. R^2	0.663

Note: Results are from a logistic regression computing (18). Observations are Fannie Mae 30-Year MBS (FNM30) data (source: eMBS) and the sample is Jan 1994 - Jan 2015. A single observation is a pool of all mortgages with a given coupon rate, ranging from 2.0 to 17.0. The procedure is weighted least squares, where the weight for each coupon bin is the total face value of mortgages in that bin. Standard errors, displayed in parentheses, are corrected for heteroskedasticity.

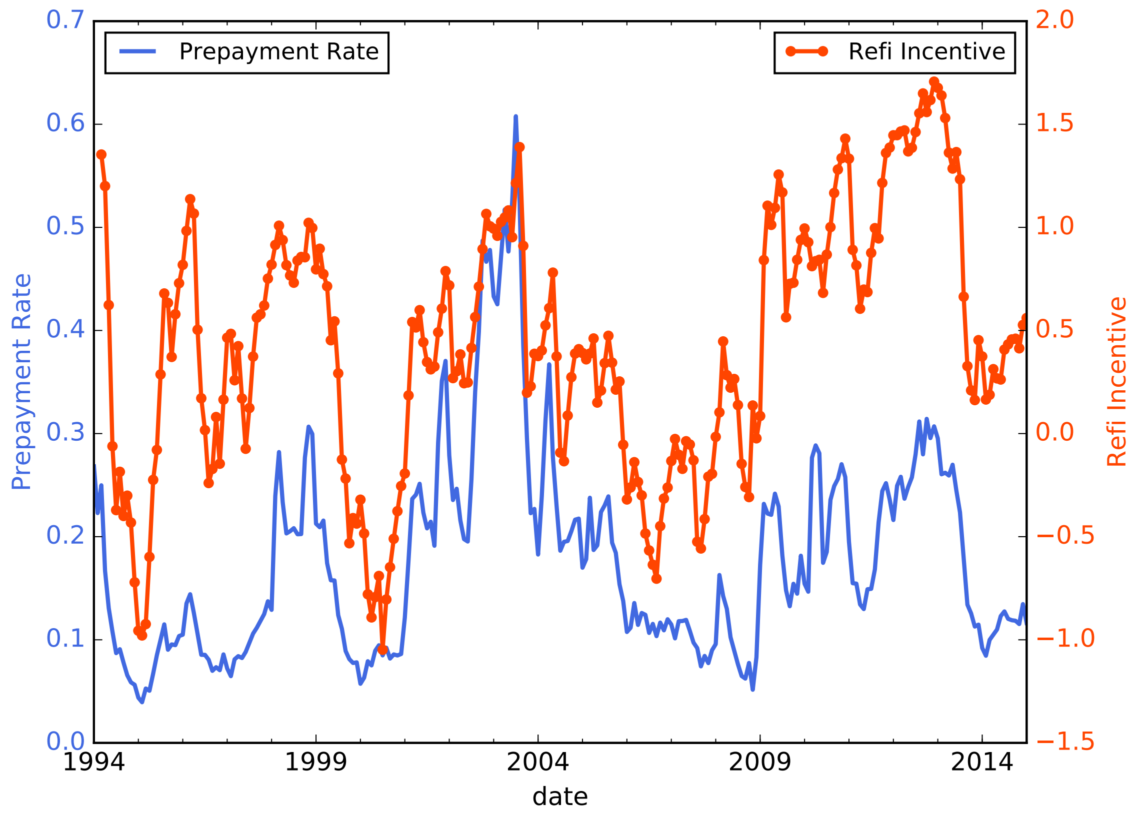
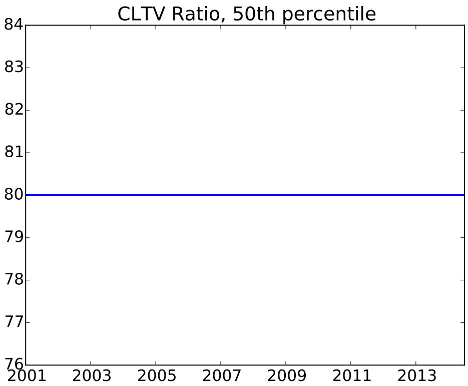
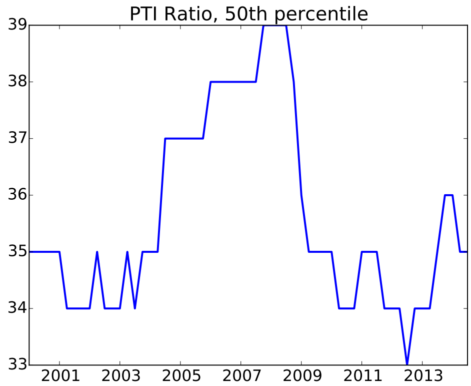


Figure A.1: Prepayment Rate vs. Interest Rate Incentive

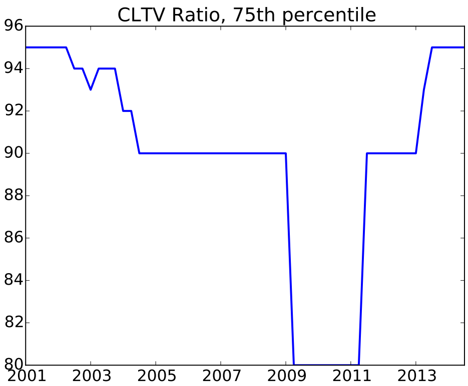
Note: "Prepayment Rate" is the conditional prepayment rate, which is an annualized rate measuring what fraction of loans would be prepaid if the *monthly* prepayment rate continued for an entire year. "Rate Incentive" is the percent spread between weighted average coupon rates on existing loans in Fannie Mae 30 Year MBS pools (FNM30), and on newly issued loans in the same pools. The value represents the approximate interest savings that a borrower would obtain by refinancing. The source for all data is eMBS.



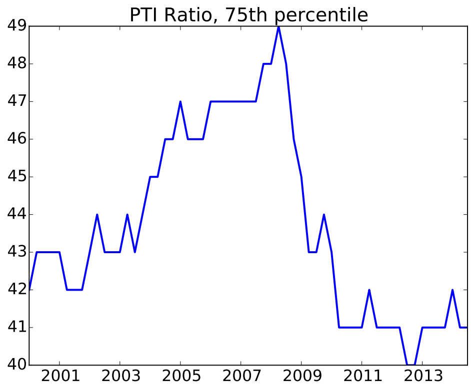
(a) CLTV: 50th Percentile



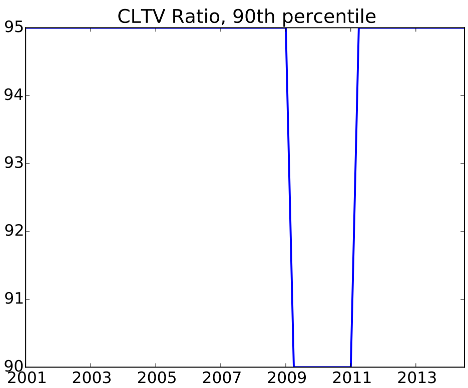
(b) PTI: 50th Percentile



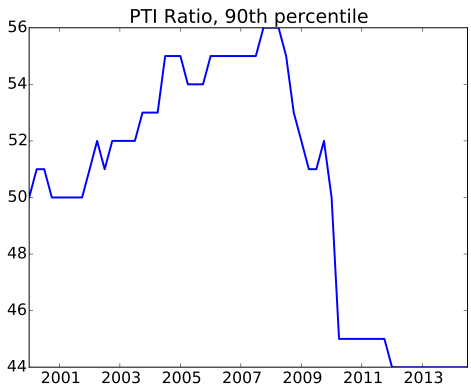
(c) CLTV: 75th Percentile



(d) PTI: 75th Percentile



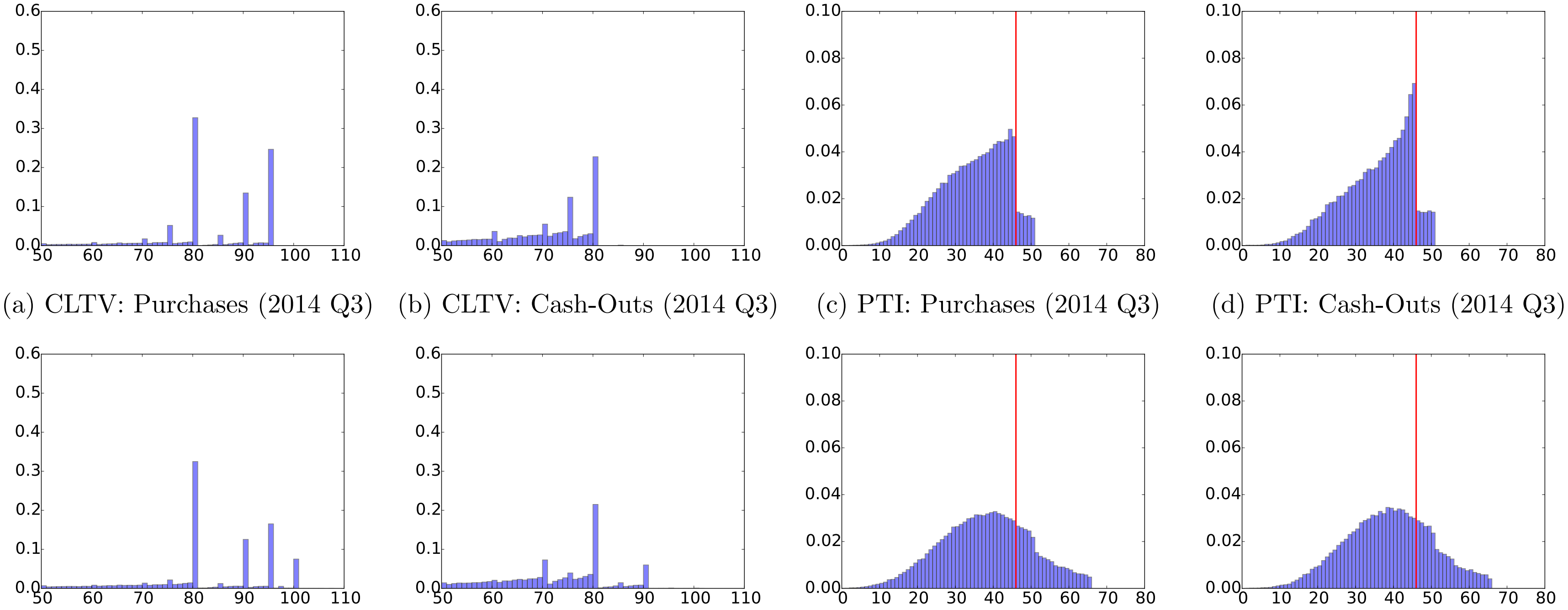
(e) CLTV: 90th Percentile



(f) PTI: 90th Percentile

Figure A.2: Fannie Mae: CLTV and PTI Percentiles for Newly Originated Purchase Mortgages

Note: [source] Source: Fannie Mae Single Family Loan Performance Dataset, issuance data.



(a) CLTV: Purchases (2014 Q3) (b) CLTV: Cash-Outs (2014 Q3) (c) PTI: Purchases (2014 Q3) (d) PTI: Cash-Outs (2014 Q3)

(e) CLTV: Purchases (2006 Q1) (f) CLTV: Cash-Outs (2006 Q1) (g) PTI: Purchases (2006 Q1) (h) PTI: Cash-Outs (2006 Q1)

Figure A.3: Freddie Mac: PTI on Newly Originated Mortgages

Note: Histograms are weighted by loan balance. Source: Freddie Mac Single Family Loan-Level Dataset.

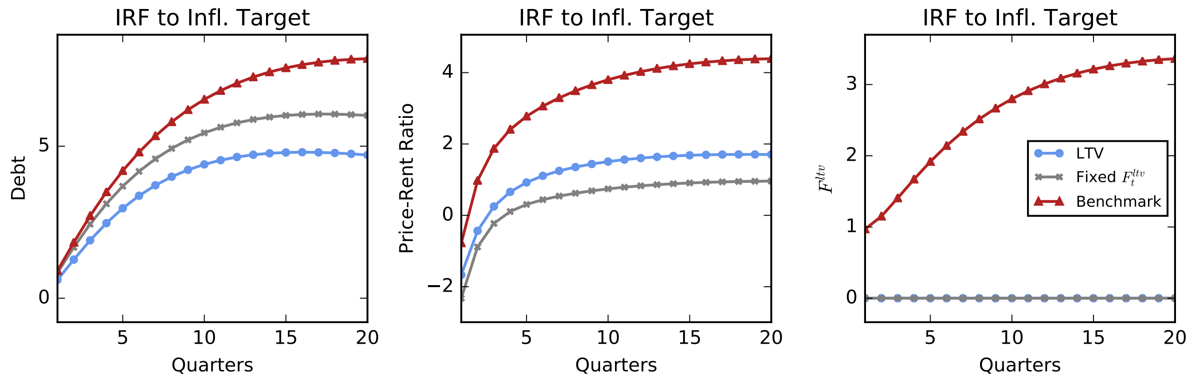


Figure A.4: Impulse Response to -1% (Annualized) Inflation Target Shock: Comparison of LTV, Benchmark, and Fixed F_t^{ltv} Economies

A value of 1 represents a 1% increase relative to steady state, except for F^{ltv} which is measured in percentage points.

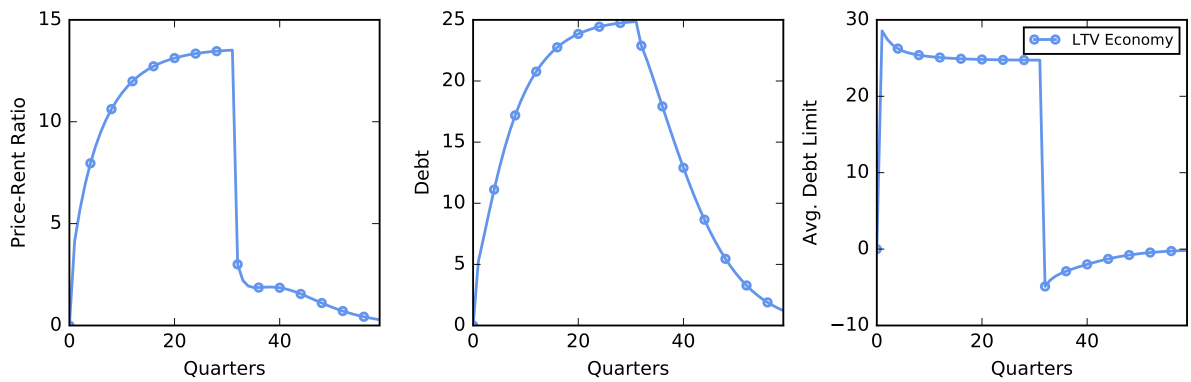


Figure A.5: Credit Loosening Experiment: LTV Economy

Note: A value of 1 represents a 1% increase relative to steady state. At time zero, the LTV limit θ^{ltv} is unexpectedly loosened from 70% to 80%, and after 32Q, is unexpectedly tightened from 80% to 70%.

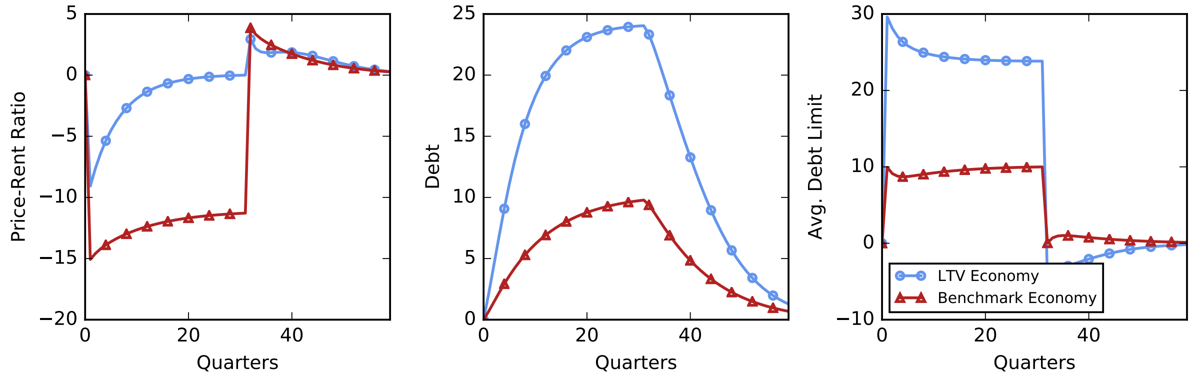


Figure A.6: Housing Preference Experiment: LTV Economy vs. PTI Economy

Note: A value of 1 represents a 1% increase relative to steady state. For both paths: at time zero, the housing preference parameter ξ is unexpectedly increased by 25%, and after 32Q is returned to its baseline value.

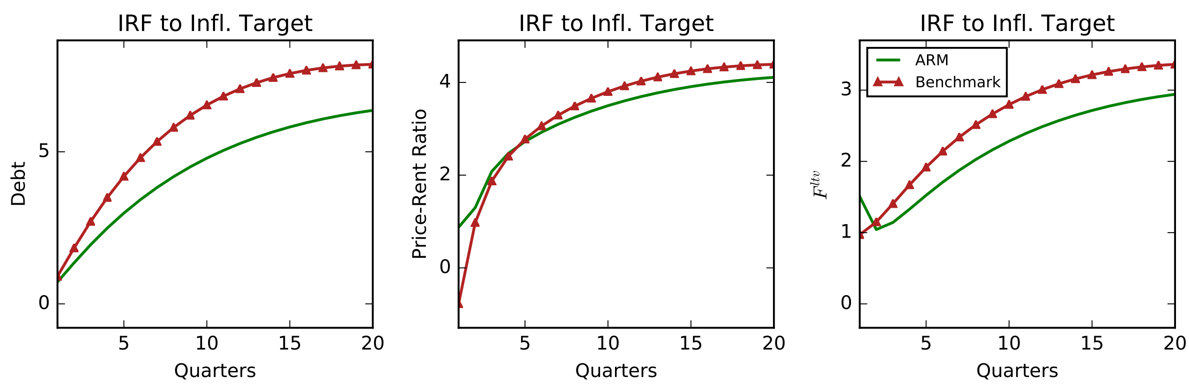


Figure A.7: Impulse Response to -1% (Annualized) Inflation Target Shock: Comparison of FRM, ARM Economies

A value of 1 represents a 1% increase relative to steady state, except for F^{ltv} which is measured in percentage points.

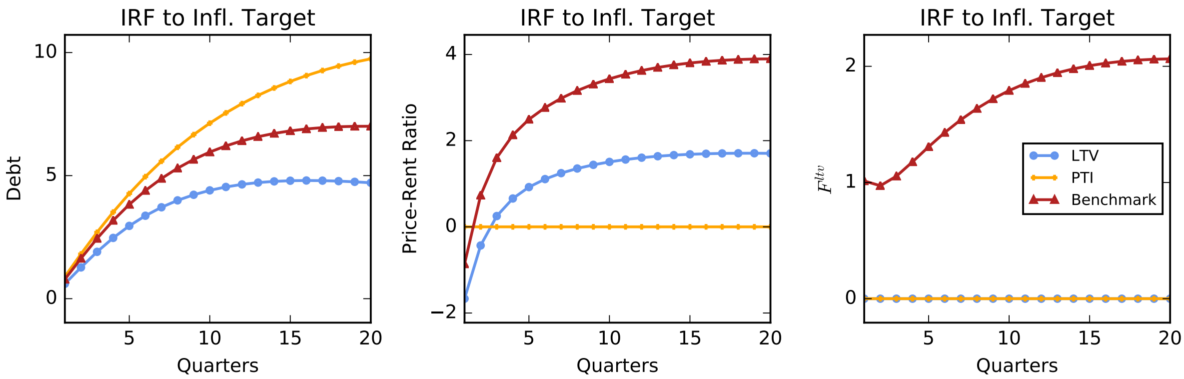


Figure A.8: Impulse Response to -1% (Annualized) Inflation Target Shock: Comparison of LTV, PTI, Benchmark Economies, Dodd-Frank (43%) PTI Limit

A value of 1 represents a 1% increase relative to steady state, except for F^{ltv} which is measured in percentage points.

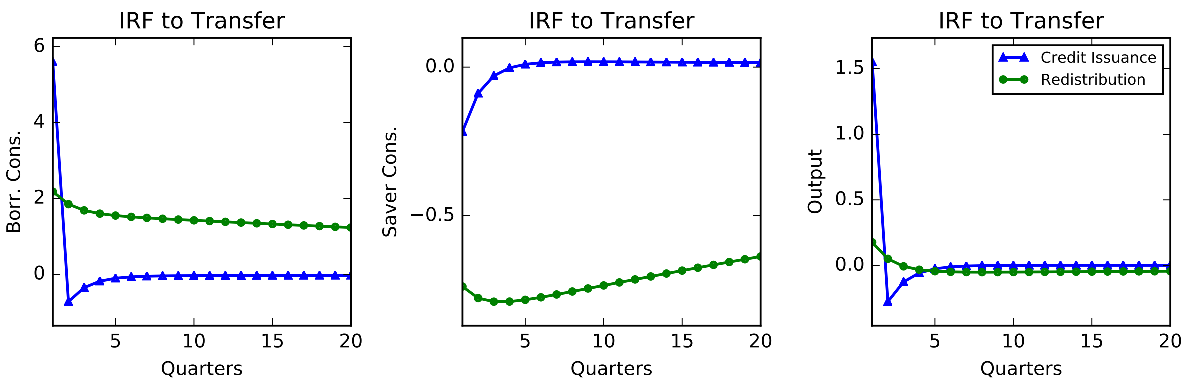


Figure A.9: Impulse Response to 1% Credit Issuance, Redistribution Shocks (Simple Model).

Note: A value of 1 represents a 1% increase relative to steady state.