The Mortgage Credit Channel of Macroeconomic Transmission*

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Abstract

This paper investigates if, how, and when mortgage credit growth propagates and amplifies shocks to the macroeconomy, and evaluates the implications of these dynamics for monetary and macroprudential policy. I develop a general equilibrium framework with endogenous prepayment decisions by borrowers and two credit constraints: a loan-to-value constraint, and a limit on the ratio of mortgage payments to income. This realistic structure delivers powerful transmission from interest rates, into mortgage credit growth, house prices and aggregate demand. The keys to transmission are a *constraint switching effect* through which changes in which constraint binds for borrowers cause large movements in house prices, and a *frontloading effect* through which waves of prepayment transmit movements in credit limits into the real economy. 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 alone, calibrated to loan-level data, can generate roughly half of the observed increase in price-rent (43%) and debt-to-household-income (53%) ratios, while relaxation of loan-to-value standards generates a much smaller boom. A cap on payment-to-income ratios, not loan-to-value ratios, is found to be the more effective macroprudential policy for limiting boom-bust cycles.

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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, residential investment, 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 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, the size of a new loan 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

[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).

[2]The "payment-to-income" (PTI) ratio is also commonly known as the "debt-to-income" or "DTI"

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 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 displayed in Figure 1: 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 models, in which debt levels are mechanically determined by 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.

Incorporating these features into the modeling framework reveals the mortgage credit channel as a powerful transmission mechanism from interest rates, through credit growth, into house prices and aggregate demand. The channel is characterized by three main findings. First, I find that the addition of PTI limits and endogenous prepayment greatly amplifies the effect of interest rate fluctuations on credit growth. At the intensive margin, PTI limits are highly sensitive to movements in interest rates. Because of the structure of mortgage payments, a 1% decrease in the mortgage interest rate reduces a borrower's monthly mortgage payments, and therefore increases the amount she can borrow subject to her PTI limit, by up to 10%. This sensitivity is magnified by parallel movements at the extensive margin, since lower interest rates on new loans increase borrower incentives to prepay, encouraging issuance of new loans. These forces interact: if PTI limits loosen, borrowers are able to obtain more additional debt by taking out a new loan, making

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.

[3]This includes any paper that linearizes around a steady state in which borrowers are at their LTV limits, (e.g., Iacoviello (2005), among many others), as well as papers that adjust borrowing limits to account for "ratchet effects" of past debt (e.g., Justiniano, Primiceri, and Tambalotti (2015b)).

it easier to justify the transaction cost of new issuance. Combined, these forces nearly double the effect of a 1% productivity shock on credit growth (from 0.86% to 1.45%) at a horizon of 20Q.

In a second finding, the interaction between PTI and LTV limits creates a novel channel through which interest rates influence house prices, which would not be present under either constraint in isolation: the *constraint switching effect.* Relative to a borrower constrained by PTI, a borrower constrained by LTV is willing to pay a premium for additional housing, as this allows her to obtain a larger loan. Any shock that causes a fall in interest rates loosens PTI limits, so that many borrowers who were formerly constrained by PTI may now find LTV to be more restrictive. As a result, more borrowers are willing to pay a collateral premium for housing, leading to a rise in housing demand, and pushing up price-rent ratios by up to 4% in response to a persistent 1% fall in nominal interest rates. Since a loosening of PTI limits causes house prices to rise, this movement also endogenously loosens LTV limits, amplifying the impact of movements in PTI limits on credit growth. Due to this amplification, the benchmark economy with both LTV and PTI limits displays debt dynamics closer to that of an economy with PTI only, despite the fact that only a minority of borrowers are constrained by PTI at equilibrium.

My third finding is that endogenous changes in prepayment rates can greatly amplify transmission into output. Borrowers in the model have higher marginal propensities to consume than savers, so that credit growth stimulates demand. But in this class of New Keynesian model, output responds most to changes in short-run demand, before firms have an opportunity to adjust their prices. When interest rates fall, many borrowers choose to obtain new loans, generating a wave of new credit issuance, and a large output response on impact, which I call the *frontloading effect.* In contrast, if borrowers always prepaid at the average rate, borrowing would occur at a much more gradual pace, with new spending occurring too late to affect output. Quantitatively, I find that incorporating endogenous prepayment increases the impact of a 1% technology shock on output by nearly 50% (from 0.52% to 0.76%).

I apply these results to two topics with direct policy relevance. First, I demonstrate that the mortgage credit channel strengthens the ability of monetary policy to stabilize inflation, requiring smaller movements in the policy rate to return to target after a shock. For example, a fall in rates to counter deflationary pressures increases credit growth through the mortgage credit channel, spurring demand and pushing prices up, thus making the cut in rates more potent. Experiments imply that in response to persistent shocks, the required movement in the policy rate may be only a small fraction of that in a model without PTI limits or endogenous prepayment, and can

even take the opposite sign on impact. However, these smaller interest rate movements induce *larger* swings in debt and house prices, roughly doubling the response of credit growth. This finding reveals a potentially important dilemma likely faced by policymakers in the early 2000s, as correcting imbalances in inflation may worsen imbalances in credit markets.

As a second application, I use the model to investigate the sources of the boom and bust and the implications for macroprudential policy. PTI limits were greatly relaxed during the housing boom, resulting in a massive increase in the PTI ratios on new loans that far outstripped the growth in LTV ratios over this period. Due in part to these events, regulation of PTI ratios has become a central focus of policymakers, leading to a cap on allowable PTI ratios as the central mortgage market regulation in the Dodd-Frank financial reforms.[4] Using the model, I show that a liberalization of LTV and PTI limits over this period can reproduce accounting for 43% of the increase price-rent ratios and 53% of the increase in debt-to-household-income ratios observed during the boom. These effects are almost entirely driven by the relaxation of PTI limits. A counterfactual scenario loosening PTI limits alone can generate nearly the entire effect of the full liberalization of both constraints on house prices, and most of the impact on debt. In contrast, relaxing the LTV constraint while leaving the PTI limit unchanged causes debt to rise only slightly and — through the constraint switching effect — cause house prices and price-rent ratios to *fall*. This result demonstrates the effectiveness of a cap on PTI ratios as a tool to limit the amplitude of the boom-bust cycle.

Finally, while I have focused on the consequences for credit growth, this paper's realistic mortgage structure also has implications for redistribution, since prepayment changes the interest rate on existing debt. Although recent research has shown that changes in interest payments can have important aggregate effects in adjustable-rate mortgage economies, I demonstrate that these redistributions have minimal impact on aggregate variables in a fixed-rate environment, even though the total transfer of wealth can be large in present value.[5] I find that the key determinant of the aggregate effect of redistribution is persistence. In the case of prepayment, the near-permanent change in interest flows alters the constrained borrower's *current* income, and the patient saver's *permanent* income by approximately equal magnitudes, leading to offsetting demand responses by borrowers and savers. This result indicates that recent mortgage market interventions that adjust only the rate and not the balance of a loan are therefore unlikely to generate large stimulus.[6]

[4] The Dodd-Frank Wall Street Reform and Consumer Protection Act.

[5] Examples include Rubio (2011), Calza, Monacelli, and Stracca (2013), Garriga, Kydland, and Sustek (2015), and Auclert (2015).

[6] Most prominent is the Home Affordable Refinance Program.

Literature Review

This paper builds on several existing strands of the literature.[7] The first is a rapidly growing class of empirical work on the relationship between mortgage credit, house prices and economic activity, particularly during the boom and bust. These works include Adelino, Schoar, and Severino (2015a), Adelino, Schoar, and Severino (2015b), Adelino, Schoar, and Severino (2015c), Aladangady (2014), Di Maggio and Kermani (2015), Favara and Imbs (2015), Mian and Sufi (2008), Mian and Sufi (2014). My work also connects to empirical studies borrower prepayment behavior, including Andersen, Campbell, Nielsen, and Ramadorai (2014) and Keys, Pope, and Pope (2014). In this paper, I construct a framework that allows analysis of many of the empirical insights contained in this work in a general equilibrium setting.

Turning to general equilibrium models, this paper connects to work on endogenous borrowing limits in macroeconomics. Beginning with Kiyotaki and Moore (1997), and adapted to the case of housing by Iacoviello (2005), an impressive body of scholarship has emerged incorporating housing and collateral constraints into a monetary DSGE environment, including Calza et al. (2013), , Garriga et al. (2015), Iacoviello and Neri (2010), Liu, Wang, and Zha (2013), and Rubio (2011). My paper builds on this tradition by enriching the mortgage structure: introducing the PTI limit alongside the LTV limit and incorporating endogenous prepayment allows for new transmission channels with important effects on dynamics.

Next, a number of heterogeneous agent models have analyzed the impact of transaction costs on the housing, mortgage, and related financial decisions of households, including Kaplan and Violante (2014) for a general asset; Laufer (2013) and Gorea and Midrigan (2015) for one-period debt; and Campbell and Cocco (2015), Chatterjee and Eyigungor (2015), Chen, Michaux, and Roussanov (2013), Guler (2014), Elenev, Landvoigt, and Van Nieuwerburgh (2015), and Landvoigt (2015) for the case of long-term mortgages. Khandani, Lo, and Merton (2013) use a detailed reduced-form model of mortgage and housing markets to analyze the effect of mortgage refinancing on systemic risk. By providing a highly tractable model of borrowing frictions that allows for closed-form solutions, my paper allows these dynamics to be embedded in a monetary DSGE environment with a full set of aggregate shocks.

Several other papers, including Campbell and Hercowitz (2005), Favilukis, Ludvigson, and Van Nieuwerburgh (2010), Favilukis, Kohn, Ludvigson, and Van Nieuwerburgh (2012), Iacoviello

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

and Pavan (2013), and Favilukis, Ludvigson, and Van Nieuwerburgh (2014) build rich models of housing and collateralized debt in the presence of aggregate shocks. While offering important insights about housing dynamics and the role of credit market liberalization and tightening in driving the housing boom and bust, these papers use one-period real debt that can be freely adjusted up to a LTV limit, abstracting from the realistic debt dynamics that are at the heart of my study.

I reserve three papers for special mention due to their high degree of relevance to this project. First, Auclert (2015) characterizes the *redistribution channel* of monetary policy, through which changes in real interest rates redistribute wealth by changing the payments on the existing stock of debt. This channel is complementary to, but separate from, the mortgage credit channel, which generates its effects by changing the *stock* of debt holding the payments per unit of debt fixed. Although this channel is quantitatively weak in my framework with prepayable fixed-rate mortgages, Auclert (2015) shows that it can deliver large effects in response to transitory shocks when borrowers hold adjustable-rate mortgages. While I focus on the impact of the mortgage credit channel — the main contribution of this paper — other channels are certainly at work, both in the model as well as in the actual economy.

Second, Corbae and Quintin (2013) is, to my knowledge, the only other theoretical macroeconomic work to employ a PTI constraint and to model its relaxation as a cause of the housing boom. However, Corbae and Quintin (2013) 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, which I do not consider, 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.

Finally, Justiniano, Primiceri, and Tambalotti (2015a) 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 endogenous movements in interest rates — the cornerstone of the channel I consider — and provide a novel aggregation method to allow for underlying heterogeneity among borrowers. Moreover, by focusing on PTI limits, I am able to provide new insights into the sources of the recent boom-bust, by calibrating a transition path to match observed

relaxations of PTI standards in the data, as well as analysis of the effects of the PTI cap imposed by Dodd-Frank.

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 2.2 provides a simple example demonstrating the properties of the model from an individual borrower's perspective. Section 5 presents the quantitative properties of the model. Section 6 discusses the implications of these results for monetary and macroprudential policy, and the sources of the boom and bust. Section 7 considers the redistributive effects of prepayment, with comparison to the redistribution channel literature. Section 8 concludes. Additional results and extensions can be found in the online appendix.[8]

2 LTV and PTI Constraints

This section describes the source of LTV and PTI constraints, and their empirical properties in the data.

2.1 Introduction to Underwriting

While in the model I treat the LTV and PTI constraints facing borrowers as exogenous and institutional, the roots 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

[8]The online appendix can be found at dlgreenwald.com/Greenwald_JMP_Appendix.pdf.

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. 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.[9] The underwriting criteria set by the GSEs are generally thought of as the industry standard, and are often emulated by banks issuing loans for their own portfolios. First, let us consider LTV limits.[10] 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 two limits (36% or 45%) for PTI, where which one applies depends on the borrower's 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

[9] 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.

[10] 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.

more important measure in practice. However, since I do not have other forms of recurring debt payments aside from mortgages, I will impose front-end PTI limits in the model, and calibrate them accordingly.

2.2 Simple Numerical Example

To provide an example of LTV and PTI constraints in action, as well as to preview the core mechanisms of the model, I present a simple example that demonstrates this key mechanism of the model from an individual's perspective. Consider a prospective home-buyer who enjoys housing services, but prefers to keep her assets liquid, and therefore prefers to make a smaller down payment. Her income is $50,000 per year, and so her maximum payment under a 28% PTI limit is $1,167 per month. At an interest rate of 6%, this maximum payment is associated with a loan size of $160,000, meaning that she is free to borrow up to this amount without exceeding her PTI constraint. Her maximum LTV ratio is 80%, which requires her to pay a minimum of 20% of the value of the house in down payment.[11]

The borrower's choice set is shown in Figure 2a. The blue line represents the amount of down payment that the borrower must make for a house of a given price. Note the kink at price $200,000: below this point, the borrower can make the minimum down payment, paying only 20 cents on the dollar down. In this region, buying a house costing $1 more allows her to borrow an additional 80 cents, loosening her overall borrowing limit. However, since the borrower cannot obtain a loan larger than $160,000 due to her PTI limit, increases in price beyond $200,000 do not allow for additional debt, and so she must pay dollar-for-dollar above this amount in down payment. While the borrower's ultimate decision hinges on her preferences, it seems likely that many would be drawn to the corner solution at a price of exactly $200,000. This decision need not follow from any advanced calculation on the part of the borrower, as it is easy to imagine the corner solution (House #2) as an intuitive choice from the following menu

	Price	Down Payment
House #1	$175,000	$35,000
House #2	$200,000	$40,000
House #3	$225,000	$65,000

which features a much larger change in down payments switching from House #2 to House #3 relative to switching from House #1 to House #2. If many borrowers prefer a corner solution in

[11] I round all house prices and loan sizes to the nearest $1,000 for this example.

this fashion, then the interaction of constraints can have large effects on demand.

From this starting point, assume that the mortgage interest rate now falls from 6% to 5%. The effect of this interest rate is displayed in Figure 2b, where the dashed lines represent the down payment schedule under the new interest rate. After the change, the borrower's maximum monthly payment of $1,167 now corresponds to a loan of size $178,000. This large decrease in the credit limit of 11% in response to a 1% change in the interest rate is demonstrative of the high sensitivity of the PTI constraint to interest rates, discussed at length in Section 5. This higher maximum loan size implies that the kink at which the borrower must begin paying dollar-for-dollar in down payment now occurs at house price $223,000. Since a borrower who changes her preference in this way increases the amount she is willing to spend on a house by 11%, a substantial rise in housing demand may result. Note that this effect occurs because of the changing collateral value of housing: house value that previously could not be used as collateral to obtain additional debt became usable due to a loosening PTI constraint.

To demonstrate the response to changes in credit standards, we can instead keep the interest rate fixed at 6% and see what happens when the maximum PTI ratio is relaxed from 28% to 31%, shown in Figure 2c. As in the case of the fall in the interest rate, this change expands borrowers' PTI limits, allowing more credit and raising the kink house price. In contrast, keeping the PTI ratio fixed and increasing the maximum LTV ratio from 80% to 90%, shown in Figure 2d, has a sharply different impact. While the borrower's maximum loan size under PTI remains at $160,000, the house price at which her loan reaches this size decreases to $178,000 (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*. One 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.

2.3 LTV and PTI in the Data

With the underwriting standards described in Section 2.1 in mind, we can consider their impact in the data. Figures 3 and 4 show the distribution of 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).[12] First, let us consider the plots for 2014, which are likely to be more indicative of lending standards in the near future, beginning with purchase loans.[13] Figure 3b shows that the CLTV ratios on purchase loans display very clear spikes at well-known institutional limits: the 80% PMI threshold discussed above, 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 4b. 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 down payment, which is the corner solution of Section 2.2. 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.

If a borrower pursues this strategy, she will end up with a house with value less than or equal to her threshold price. As a result, if the borrower then obtains the largest loan possible, she will end up being constrained by her LTV limit, since the PTI limit only begins to bind at the threshold. As a result, the borrower's loan will be issued at an institutional LTV limit, but may be slightly below the institutional PTI limit — consistent with the clear spikes in Figure 3b, and the smoother shape in 4b. However, the PTI limit may still have been highly influential on housing demand, by influencing the target house price — the maximum price that the borrower is willing to pay. In this way, many borrowers may in practice be constrained by PTI, despite the lack of a single large spike at the institutional limit.[14]

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

[12] All PTI ratios are back-end ratios, as defined in Section 2.1.

[13] 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.

[14] 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 buy than their income or the interest rate.

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 4d to Figure 4b. 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 3d to Figure 3b, with much more mass between spikes for cash-out loans.

Although the data described above suggest that many borrowers are currently influenced by PTI constraints — a number likely to rise further as interest rates increase from recent historic lows — circumstances during the recent housing boom appear strikingly different. From Figures 4a and 4c, we can see that observed PTI ratios during the boom period (2006 Q1) do not appear to be limited by any institutional constraint for both purchase and cash-out loans, with many loans taking on enormous PTI ratios.[15] These plots are suggestive of very loose PTI standards during the housing boom. In contrast, the distribution of CLTV ratios do not appear remarkably different, implying that the more dramatic shift may have occurred in PTI limits.

Evidence for this shift in PTI standards can be found in Figure 5, 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) calculates that the 75th percentile of the PTI distribution over the period 1988-1991 was below 36%. As shown in Figure 5d, 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. Using similar data, Bokhari, Torous, and Wheaton (2013) find that only 5% of Fannie Mae loans had a PTI of over 42% in 1993 — a fraction that had risen to 27% by the start of my sample, and to a maximum of 41% in 2007. In contrast, CLTV ratios appear largely flat over the boom, suggesting a less sharp change in LTV standards relative to PTI standards.[16]

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

[16] Lee, Mayer, and Tracy (2012) provide evidence that in many areas, "piggyback" second liens drove a large increase in CLTVs. However, it appears likely given the evidence in Figure 5 that combined PTI ratios for these loans were expanded by even more than the CLTV limits.

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, denoted "borrowers," while the other family contains relatively patient households, denoted "savers." For notation, let subscript b denote borrower variables, and let subscript s denote saver variables. These labels are based on equilibrium behavior, as aside from preferences there is no technological difference between the two families. To allow for potentially different relative sizes of the two groups, let χ_b denote the measure of borrowers, and let $\chi_s = 1 - \chi_b$ denote the measure of savers. 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, so that redistribution between the two groups cannot be insured against.[17] Both types supply 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 $n_{j,t}$:

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

where utility takes the separable form

$$u(c_{j,t}, n_{j,t}, h_{j,t}) = \log(c_{j,t}/\chi_j) + \xi \log(h_{j,t}/\chi_j) - \eta \frac{(n_{j,t}/\chi_j)^{1+\varphi}}{1+\varphi}. \tag{2}$$

where scaling by the χ_j terms transforms values from levels into per-capita terms. 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, e.g.,

$$u^c_{j,t} \equiv \frac{\partial u(c_{j,t}, n_{j,t}, h_{j,t})}{\partial c_{j,t}}$$

[17] Werning (2015) documents that under log preferences (as used here), and certain assumptions regarding the structure of idiosyncratic shocks, an incomplete markets economy with idiosyncratic risk can yield an aggregation consistent with a representative agent's Euler equation, with the effects of market incompleteness inducing a change from the individual to the aggregate discount factor β_j.

with symmetric expressions for $u^n_{j,t}$ and $u^h_{j,t}$, and define each type's *stochastic discount factor* $\Lambda_{j,t+1}$ by

$$\Lambda_{j,t+1} \equiv \beta_j \frac{u^c_{j,t+1}}{u^c_{j,t}}$$

which measures how much an agent of type j values real payments at time $t+1$. Finally, it is useful to define the *nominal stochastic discount factor* $\Lambda^{\$}_{j,t+1}$ by

$$\Lambda^{\$}_{j,t+1} \equiv \pi^{-1}_{t+1}\Lambda_{j,t+1}$$

which measures how much an agent of type j values nominal payments at time $t+1$.

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.[18] 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, but extend the model for the case of adjustable-rate mortgages in the online appendix. Under a fixed-rate

[18] For example, the average coupon rate on existing loans q_t is a weighted average over many past rates at origination q^*_{t-k}.

mortgage contract, the borrower pays fraction ν of the remaining principal balance each period, so that next period's principal balance and payment both decay by factor $(1-\nu)$. 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. Note that the principal balance after k periods is $\$(1-\nu)^k$ and that the average maturity of debt is ν^{-1}.

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.[19] Each borrower can hold at most one mortgage, so that in order to obtain a new loan, a borrower must prepay her old loan. I verify that, at equilibrium, borrowers will always prefer to obtain a new loan when prepaying an old loan. In the model, a borrower enters the period with a mortgage contract specifying the start-of-period balance m_{t-1} and the start-of-period coupon rate on the existing loan q_{t-1},and their start-of-period holdings of housing collateral backing the loan h_{t-1}. If a borrower chooses to prepay her loan, she may choose a new house size $h_{b,t}^*$ 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. From here on, I present the model under 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]

[19]More accurately, this is standard for prime mortgage contracts, the dominant category in the US economy. For subprime mortgages, prepayment penalties are common, but since I abstract from credit risk, and since subprime mortgages are typically a small minority of mortgage debt, I do not include this distinction in the model. A thorough analysis of the theory of prepayment penalties can be found in Mayer, Piskorski, and Tchistyi (2013).

[20]This assumption dramatically simplifies the analysis, but is not strictly necessary. In the online appendix, I derive a version of the model with closed-form solutions under full heterogeneity. I focus on the simplified model, but 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.

Borrowing Limits

Each borrower is subject to an overall credit constraint $\bar{m}_{i,t}$ on the size of new loans, so that $m^*_{i,t} \leq \bar{m}_{i,t}$. This overall constraint is a function of two factors: the borrower's LTV limit $\bar{m}^{ltv}_{i,t}$, and her PTI limit $\bar{m}^{pti}_{i,t}$. These limits are in turn defined by the maximum amount of debt that can be issued while keeping the LTV or PTI ratios on new debt below institutional thresholds θ^{ltv}_t and θ^{pti}_t, respectively. These inequalities can be written for a given debt level m as

$$\frac{m}{p_{h,t} h^*_{b,t}} \leq \theta^{ltv}_t \tag{3}$$

$$\frac{(q^*_t + \tau) m}{w_t \bar{n}_{b,t} e_{i,t}} \leq \theta^{pti}_t. \tag{4}$$

where the numerator and denominator on the left hand side of (3) are the maximum loan balance and total house value, and the numerator and denominator on the left hand side of (4) are the total housing payment made by the borrower, and the borrower's income, respectively. The term τ represents taxes, insurance, and other borrowing costs which are counted toward the mortgage payment. The notation $\bar{n}_{b,t}$ implies that the borrower treats this value as fixed when choosing her labor supply, as otherwise the borrower might unrealistically work a incredible amount for a single quarter expressly in order to qualify for a large loan, and then return to her normal labor supply. Finally, $e_{i,t}$ is an idiosyncratic shock to labor income with mean unity, drawn i.i.d. across borrowers and time from a distribution with c.d.f. Γ_e. These inequalities can be solved to yield the maximum debt levels m consistent with (3) and (4):

$$\bar{m}^{ltv}_{i,t} = \theta^{ltv}_t p_{h,t} h^*_{b,t} \tag{5}$$

$$\bar{m}^{pti}_{i,t} = \theta^{pti}_t w_t n_{b,t} e_{i,t} / (q^*_t + \tau). \tag{6}$$

The borrower's overall credit limit is the minimum of the two, so that

$$\bar{m}_{i,t} = \min\left(\bar{m}^{ltv}_{i,t}, \bar{m}^{pti}_{i,t}\right). \tag{7}$$

It is useful to define the aggregate or average LTV and PTI limits

$$\bar{m}^{ltv}_t = \theta^{ltv}_t p_{h,t} h^*_{b,t} \tag{8}$$

$$\bar{m}^{pti}_t = \theta^{pti}_t w_t n_{b,t} / (q^*_t + \tau) \tag{9}$$

and to note that $\bar{m}^{pti}_{i,t} = \bar{m}^{pti}_t e_{i,t}$. Next, define

$$\bar{e}_t = \frac{\theta^{ltv}_t p_{h,t} h^*_{b,t}}{\theta^{pti}_t w_t n_{b,t}/(q^*_t + \tau)} = \frac{\bar{m}^{ltv}_t}{\bar{m}^{pti}_t} \tag{10}$$

to be the threshold value of $e_{i,t}$ so that for $e_{i,t} < \bar{e}_t$, borrowers are constrained by PTI, and for $e_{i,t} > \bar{e}_t$, borrowers are constrained by LTV. With this in mind, we can define

$$\begin{aligned} F^{ltv}_t &= 1 - \Gamma_e(\bar{e}_t) \\ F^{pti}_t &= \Gamma_e(\bar{e}_t). \end{aligned}$$

to be the fractions constrained by LTV and PTI, respectively. With these definitions in mind, aggregation yields the overall credit limit

$$\begin{aligned} \bar{m}_t &= \int \min\left(\bar{m}^{pti}_t e_i, \bar{m}^{ltv}_t\right) \, d\Gamma(e_i) \\ &= \underbrace{\bar{m}^{pti}_t \int^{\bar{e}_t} e_i \, d\Gamma_e(e_i)}_{\text{PTI Constrained}} \quad + \quad \underbrace{\bar{m}^{ltv}_t (1 - \Gamma_e(\bar{e}_t))}_{\text{LTV Constrained}}. \end{aligned} \tag{11}$$

The first term in (11) represents the borrowing capacity of the fraction of households constrained by PTI, those with low income draws. For these households, their borrowing capacity is the product of the aggregate portion of the PTI limit, $\bar{m}_t$, and their income draw. Integrating over $e_i < \bar{e}_t$, yields the total borrowing capacity of these households. The second term is the borrowing capacity of LTV-constrained households, which since all borrowers have symmetrical holdings of housing, is simply the product of the aggregate LTV limit and the fraction of households constrained by LTV. Differentiating (11) shows that this overall limit has the property

$$\frac{\partial \bar{m}_t}{\partial h^*_{b,t}} = F^{ltv}_t \theta^{ltv}_t p^h_t \tag{12}$$

which intuitively is the product of the fraction of agents constrained by LTV and the amount by which an extra unit of housing relaxes the LTV limit.

3.2.3 Housing

Both borrowers and savers own housing, which produces a flow of housing services each period equal to the stock, and depreciates at rate δ. 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.[21] 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 Borrower's Problem

Due to the simplifying assumption made in Section 3.2.2, the state space for the borrower's problem allows for aggregation, and takes a simple and intuitive form. 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 pay_{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 state variables are defined by

$$m_t = \rho_t m_t^* + (1-\rho_t)(1-\nu)\pi_t^{-1} m_{t-1} \tag{13}$$

$$h_{b,t} = \rho_t h_{b,t}^* + (1-\rho_t)(1-\delta) h_{b,t-1} \tag{14}$$

$$\text{pay}_t = \rho_t q_t^* m_t^* + (1-\rho_t)(1-\nu)\pi_t^{-1} \text{pay}_{t-1} \tag{15}$$

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 solve

$$V_b(m_{t-1}, h_{b,t-1}, \text{pay}_{t-1}) = \max_{c_{b,t}, n_{b,t}, m_t^*, h_{b,t}^*, \rho_t} u(c_{b,t}, h_{b,t}, n_{b,t}) + \beta_b \mathbb{E}_t V_b(m_t, h_{b,t}, \text{pay}_t) \tag{16}$$

subject to the budget constraint

$$\begin{aligned} c_{b,t} \leq\ & w_t n_{b,t} - \pi_t^{-1} \text{pay}_{t-1} + \rho_t \left(m_t^* - (1-\nu)\pi_t^{-1} m_{t-1} \right) \\ & - \rho_t p_t^h \left(h_{b,t}^* - (1-\delta) h_{b,t-1} \right) - \left(\text{Cost}(\rho_t) - \text{Rebate}_t \right) m^* \end{aligned} \tag{17}$$

[21] The fixed saver demand can be equivalently interpreted as segmented housing markets among borrowers and savers, which can also be interpreted as geographic variation, where the two types occupy houses in different areas and cannot move between areas. In this case, the overall house price in the model corresponds to the price of housing in borrower areas.

the debt constraint $m_t^* \leq \bar{m}_t$, and the laws of motion (13) - (15), where

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

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.[22]

3.4 Saver's Problem

The representative saver chooses consumption $c_{s,t}$, labor supply $n_{s,t}$, the size of newly purchased houses $h_{s,t}$, and the face value of newly issued mortgages m_t^* to solve

$$V_s(m_{t-1}, h_{s,t-1}, \text{pay}_{t-1}) = \max_{c_{s,t}, n_{s,t}, h_{s,t}, m_t^*} u(c_{s,t}, h_{s,t}, n_{s,t}) + \beta_s \mathbb{E}_t V_s(m_t, h_{s,t}, \text{pay}_t) \tag{18}$$

subject to the budget constraint

$$\begin{aligned} c_{s,t} \leq \Pi_t + w_t n_{s,t} - \rho_t(m_t^* - (1-\nu)\pi_t^{-1} m_{t-1}) + \pi_t^{-1} \text{pay}_{t-1} \\ - p_t^h (h_{s,t} - (1-\delta) h_{s,t-1}) - R_t^{-1} b_t + b_{t-1} \end{aligned} \tag{19}$$

and the laws of motion (13), (15), where Π_t are intermediate and construction firm profits. The saver takes the fraction of loans prepaid ρ_t as given, since this is chosen by the borrower. 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.

3.5 Productive Technology

The production side of the economy is populated by a continuum of intermediate goods producers and a final good producer. These familiar elements of the New Keynesian framework are the standard setting in which to introduce nominal rigidities.

[22] Similar to the approach in Garriga et al. (2015), I choose to rebate these costs to borrowers. I do so out of consideration that these costs may stand in for non-monetary frictions in refinancing. As documented in Andersen et al. (2014) and Keys et al. (2014) , among others, borrowers often do not prepay their mortgages even when it is in their financial interest to do so. Calibrating the cost distribution Γ_κ can capture the level and sensitivity of prepayment in the data, but likely implies costs above the true financial costs of the transaction as a result (although they are similar to the costs of buying or selling a new house). In the calibration, as in Gorea and Midrigan (2015), I find that relatively large transactions costs are required to match the rate of prepayment.

3.5.1 Final Good Producer

The final good producer operates the production function

$$y_t = \left[\int y_t(i)^{\frac{\lambda-1}{\lambda}} \, di \right]^{\frac{\lambda}{\lambda-1}}. \tag{20}$$

where each input $y_t(i)$ is purchased from an intermediate goods producer at price $P_t(i)$. The final good producer's problem is therefore given by

$$\max_{y_t(i)} P_t \left[\int y_t(i)^{\frac{\lambda-1}{\lambda}} \right]^{\frac{\lambda}{\lambda-1}} - \int P_t(i) y_t(i) \, di \tag{21}$$

where P_t is the price of the final good. At the optimum, the final good producer's demand for variety i, given price $P_t(i)$, is given by

$$y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\lambda} y_t. \tag{22}$$

Integrating over varieties, the price of the final good can be read off of the equation

$$P_t = \left[\int P_t(i)^{1-\lambda} \right]^{\frac{1}{1-\lambda}}. \tag{23}$$

3.5.2 Intermediate Goods Producers

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

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

where $n_t(i)$ represents labor demand, to meet the final good producer's demand for good i given that price. Intermediate firms are subject to price stickiness of the Calvo-Yun form with indexation. Specifically, a fraction $1 - \zeta_p$ of firms are able to adjust their price each period, while the remaining fraction ζ_p update their existing price by the rate of steady state inflation.

3.5.3 Total Factor Productivity

Total factor productivity a_t follows the stochastic process

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

3.5.4 Construction Sector

A representative construction firm owned by the savers produces new houses. The construction firm can convert the final consumption good into new housing x_t^h, but must pay quadratic adjustment costs, so that

$$\max_{x_t^h} p_t^h x_t^h - x_t^h - \frac{1}{2}\zeta_h \left(\frac{x_t^h}{h_{t-1}} - \delta\right)^2 h_{t-1}$$

defines the firm's profit maximization problem.

3.6 Monetary Policy

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

$$\begin{aligned} \log R_t = \log \bar{\pi}_t + \phi_r(\log R_{t-1} - \log \bar{\pi}_{t-1}) \\ + (1-\phi_r)\Big[(\log R^{ss} - \log \pi^{ss}) + \psi_\pi(\log \pi_t - \log \bar{\pi}_t) + \psi_y(\log y_t - \log y^{ss})\Big] \end{aligned} \tag{24}$$

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

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

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 inflation target shocks are needed for monetary policy to move long rates.

In the limit $\psi_\pi \to \infty$, the rule (24) collapses to

$$\pi_t = \bar{\pi}_t \tag{25}$$

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 $(m_{t-1}, q_{t-1}, h_{b,t-1}, h_{s,t-1})$, allocations $(c_{j,t}, n_{j,t}, h_{j,t})$, new construction x^h_t, mortgage market quantities (m^*_t, ρ_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, $(c_{s,t}, n_{s,t}, h_{s,t}, m^*_t)$ 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 (24).

5. Given house prices, x^h_t satisfies the construction sector's optimality condition (39).

6. The resource market clears:

$$y_t = c_{b,t} + c_{s,t} + x^h_t + \frac{1}{2}\zeta_h \left(\frac{x^h_{j,t}}{h_{j,t-1}} - \delta\right)^2 h_{j,t-1}.$$

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

8. The housing markets clear:

$$x^h_t = \rho_t(h^*_{b,t} - (1-\delta)h_{b,t-1}) + h_{s,t} - (1-\delta)h_{s,t-1}.$$

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

From the first order condition with respect to labor supply, we obtain the standard intratemporal condition

$$w_t = -\frac{u_{b,t}^n}{u_{b,t}^c}. \tag{26}$$

From the first order condition for new debt, $m_{i,t}^*$, we obtain

$$1 = \Omega_{b,t}^m + q_t^* \Omega_{b,t}^{pay} + \mu_t \tag{27}$$

where $\Omega_{b,t}^m$ and $\Omega_{b,t}^{pay}$ 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

$$\Omega_{b,t}^m = \mathbb{E}_t \left\{ \Lambda_{b,t+1}^{\$} \Big[(1-\nu)\rho_{t+1} + (1-\nu)(1-\rho_{t+1})\Omega_{b,t+1}^m \Big] \right\} \tag{28}$$

$$\Omega_{b,t}^{pay} = \mathbb{E}_t \left\{ \Lambda_{b,t+1}^{\$} \Big[1 + (1-\nu)(1-\rho_{t+1})\Omega_{b,t+1}^{pay} \Big] \right\} \tag{29}$$

respectively, where $\Lambda_{b,t+1}^{\$}$ is the borrower's nominal stochastic discount factor. The optimality condition (27) defines μ_t, the multiplier on the borrower's aggregate credit limit. Equation (28), defining the continuation cost of an additional dollar of face value debt, integrates over two possibilities: if the borrower prepays, she will have to repay $\$(1-\nu)$, whereas if the borrower does not prepay, she will carry an extra $\$(1-\nu)$ of face value debt into the following period. Similarly, promising an additional dollar of payments, whose continuation cost is defined by (29), requires a certain \$1 payment in the next period, and promises an additional $\$(1-\nu)$ of payment in the following period only if the borrower does not prepay (thereby canceling further payments). In models with long-term mortgages but no prepayment, only the effect on promised payments, pay_{t-1}, is relevant to the borrower's problem, and face value m_{t-1} can be removed from the state space. But when debt can be prepaid, the borrower prefers having a lower value of m_t for a given value of pay_t, since m_t is what is repaid upon prepayment.

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

$$p_t^h = \frac{u_{b,t}^h / u_{b,t}^c + (1-\delta)\mathbb{E}_t \left\{ \Lambda_{t+1} p_{t+1}^h \Big[1 - (1-\rho_{t+1})\mathcal{C}_{t+1} \Big] \right\}}{1 - \mathcal{C}_t} \tag{30}$$

where $\mathcal{C}_t$ is the marginal collateral value of housing wealth, which is the value to the borrower of the relaxation in her overall constraint obtained from an additional dollar of house value, and is

defined by

$$\mathcal{C}_t = \mu_t F_t^{ltv} \theta_t^{ltv} \tag{31}$$

The three terms in (31) represent the path through which additional collateral provides value to the borrower through a relaxed credit limit. Starting from the right, θ_t^{ltv} determines how much an additional dollar of housing collateral relaxes a borrower's LTV limit. The next term, F_t^{ltv} is the fraction of borrowers constrained by LTV, which reflects the effect of relaxing LTV limits on the *overall* limit $\bar{m}_t$. Finally, the term μ_t represents the value to the borrower of having the overall limit relaxed.

With this definition in mind, the appearance of $\mathcal{C}_t$ in the denominator of (30) is relatively straightforward: 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, leading to a rise in house price at equilibrium. The reason for the appearance of the term $\mathcal{C}_{t+1}$ in the numerator is perhaps more subtle and is due to the fact that debt in the model is prepaid only infrequently. As in reality, borrowers cannot change their housing stock without obtaining a new loan. Therefore, the market price of borrower housing is the value of housing to a buyer who is simultaneously obtaining a new loan, and can immediately use the house as collateral.

But because of transaction costs, most borrowers will choose not to obtain a new loan in a given period. The borrower does not have a use for housing collateral in these periods, and values the house less than a new homebuyer. To be precise, to a borrower who has chosen not to prepay, a unit of housing is worth exactly $\mathcal{C}_{t+1} p_{t+1}^h$ less than market price, where the shortfall is equal to the product of the collateral value per dollar of housing and the house price. The appearance of $\mathcal{C}_{t+1}$ in the numerator of (30) takes this possibility into account. With probability ρ_{t+1} a given borrower will prepay her loan next period, and so the marginal value of an extra unit of housing is p_{t+1}^h, the market price. With probability $1 - \rho_{t+1}$, the borrower will not prepay, in which case the unit of housing is worth the discounted rate $(1 - \mathcal{C}_{t+1}) p_{t+1}^h$.[23]

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

[23] Alternatively, $(1 - \mathcal{C}_t) p_t^h$ is the price that a house would receive on a market in which the house could not be used as collateral and must be paid for in cash.

ratio

$$\rho_t = \Gamma_\kappa \Bigg(\underbrace{(1 - \Omega^m_{b,t}) \left(1 - \frac{(1-\nu)\pi_t^{-1} m_{t-1}}{m^*_t}\right)}_{\text{new debt}} - \underbrace{\Omega^{pay}_{b,t} \left(q^*_t - \bar{q}_{t-1} \frac{(1-\nu)\pi_t^{-1} m_{t-1}}{m^*_t} \right)}_{\text{new payments}} \\ - \underbrace{\mathcal{C}_t p^h_t \left(\frac{h^*_{b,t} - h_{b,t-1}}{m^*_t} \right)}_{\text{cost of collateral}} \Bigg). \tag{32}$$

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. Next, the 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. Finally the "cost of collateral" term is due to the fact discussed above: that due to the collateral function of housing, the market price includes a premium above the present value of housing services. The borrower takes into account that part of the benefit of a new loan may be offset by the premium paid on the collateral used to back it.

4.2 Saver Optimality

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

$$w_t = -\frac{u^n_{s,t}}{u^c_{s,t}} \tag{33}$$

$$1 = R_t \mathbb{E}_t \Lambda^\$_{s,t+1} \tag{34}$$

$$1 = \Omega^m_{s,t} + \Omega^{pay}_{s,t} q^*_t \tag{35}$$

$$p^h_t = u^h_{s,t}/u^c_{s,t} + (1-\delta)\mathbb{E}_t \left[\Lambda_{s,t+1} p^h_{t+1} \right]. \tag{36}$$

where $\Omega^m_{s,t}$ and $\Omega^{pay}_{s,t}$ 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

$$\Omega^m_{s,t} = \mathbb{E}_t \left\{ \Lambda^{\$}_{s,t+1} \left[(1-\nu)\rho_t + (1-\nu)(1-\rho_{t+1})\Omega^m_{s,t+1} \right] \right\} \tag{37}$$

$$\Omega^{pay}_{s,t} = \mathbb{E}_t \left\{ \Lambda^{\$}_{s,t+1} \left[1 + (1-\nu)(1-\rho_{t+1})\Omega^{pay}_{s,t+1} \right] \right\}. \tag{38}$$

These expressions are generally identical to the equivalent terms with the borrower's problem, with the exception that savers are unconstrained ($\mu = \mathcal{C} = 0$), use a different stochastic discount factor, and have an additional optimality condition (34) from trade in the one-period bond.

4.3 Intermediate Goods Producer Optimality

The solution to the intermediate goods producer's problem is standard and can be summarized by the following system of equations

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

where $\mathcal{N}_t$ 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 Construction Firm Optimality

The optimality condition for the construction firm is given by

$$x^h_t = \left[\delta + \zeta^{-1} \left(p^h_t - 1 \right) \right] h_{t-1} \tag{39}$$

so that new construction exceeds depreciation if and only if the house price exceeds unity.

4.5 Calibration and Computation

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 lognormal, with

$$\log e_{i,t} \sim N\left(-\frac{1}{2}\sigma_e^2, \sigma_e^2\right).$$

In this case, the properties of the lognormal distribution imply the closed form expression

$$\bar{m}_t = \bar{m}_t^{pti}\Phi\left(\frac{\log \bar{e}_t - \sigma_e^2/2}{\sigma_e}\right) + \bar{m}_t^{ltv}\left[1 - \Phi\left(\frac{\log \bar{e}_t + \sigma_e^2/2}{\sigma_e}\right)\right].$$

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, and so I choose to map this parameter to the standard deviation of $\log(h_{i,t}/y_{i,t})$ ratios for new borrowers, obtained using loan-level data from Fannie Mae, averaging over the cross-sectional standard deviation for all quarters from 2000 to 2014.[24]

I calibrate the fraction of borrowers χ_b and the borrower discount factor β_b to match moments from the 2001 Survey of Consumer Finances, chosen to be a baseline before boom entered full swing. In the model, borrowers are agents who may hold wealth in home equity, but who hold no liquid assets, a categorization closely related to the "wealthy hand-to-mouth" agents of Kaplan and Violante (2014) and Kaplan, Violante, and Weidner (2014). Following their empirical work, I identify borrowers in the data to be homeowners with a mortgage, but with less than one month's income in liquid assets. These households make up 24.3% of the 2001 Survey of Consumer Finances (SCF).[25] Since savers in the model are patient investors who hold financial assets and smooth consumption, I identify savers in the data to be households that hold more than one month's income in liquid assets. These households make up 45.4% of the 2001 SCF. [26] The

[24]See the online appendix for a description of this data set. Results using loan-level data from Freddie Mac and Knowledge Decision Services were nearly identical.

[25]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.

[26]Although 51.4% of "saver" households hold a mortgage in the data, I still categorize them as savers as

remaining 30.4% of households have low liquid balances but do not hold a mortgage, and are mostly renters.[27] Since this population does not fit well into either category, I exclude them for purposes of calibration. Normalizing the proportions of identified borrowers and savers to sum to unity, I obtain the value $\chi_b = 0.35$.

The next task is to calibrate the prepayment cost distribution. For this task I will seek to fit the model parameters to match a reduced-form prepayment regression. For the distribution of κ, I choose a mixture, such that with 1/4 probability, κ is drawn from a logistic distribution, and with 3/4 probability, $\kappa = \infty$. I choose this form so 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 distribution can be microfounded by assuming staggered refinancing opportunities, or inattention. As a result, Γ_κ takes the form

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

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 consider two possible cases. In the *exogenous prepayment* case, I let $s_\kappa \to \infty$, in which case (32) collapses to $\rho_t = \bar{\rho}$. In the *endogenous prepayment* case I instead calibrate $s_k < \infty$, allowing for endogenously varying prepayment rates, as follows. Using monthly MBS data from 1994-2015 with a wide range of coupon bins at each point in time,[28] I run a prepayment regression

$$\text{logit}(cpr_{i,t}) = \gamma_{0,t} + \gamma_1(q_t^* - \bar{q}_{i,t-1}) + e_{i,t} \tag{40}$$

where i varies across coupon bins, $cpr_{i,t}$ is annualized prepayment rate,[29] q_t^* is the weighted

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 strengthen the impact of the mortgage credit channel.

[27] 75.4% of these households do not own houses.

[28] 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.

[29] The variable $prepay_{i,t}$ is measured at monthly frequency, but I convert it to quarterly observations using the transformation

$$cpr_{i,t} = 1 - (1 - monthly_{i,t})^4$$

where $monthly_{i,t}$ is the fraction of loans that prepay in a single month (also known as "single month

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.[30] 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. Since applying the logistic assumption for Γ_κ and rearranging (32) yields

$$\operatorname{logit}(\widetilde{cpr}_t) = \gamma_{0,t} - \frac{\Omega^{pay}_{b,t}}{s_\kappa}\left(q^*_t - \bar{q}_{t-1}\frac{(1-\nu)\pi_t^{-1}m_{t-1}}{m^*_t}\right) \tag{41}$$

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 $\bar{q}_{t-1}$. Given the symmetry between (40) and (41), I calibrate s_κ so that in the steady state we have $\Omega^{pay}_b/s_\kappa = \hat{\gamma}_1$, matching the sensitivities of prepayment to interest rate incentives in the model and in the regression.

This procedure yields the values $s_\kappa = 0.0330$ and $\mu_\kappa = 0.188$. These parameters imply high costs: as shown in Figure 6b, 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 (although the average value does fall within the range of reasonable costs for transacting a new house). However, it is well known in the literature on prepayment that borrowers often do not prepay even when financially advantageous, so it is unsurprising that costs above estimated financial costs of prepayment are needed to match the data.[31]

For the LTV and PTI limits, I set $\theta^{ltv} = 0.85$, and $\theta^{pti} = 0.28$. The choice of θ^{ltv} roughly matches 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 θ^{pti}, 0.28 represents the industry standard for the front-end PTI ratio, roughly corresponding to a 36% back-end ratio, the standard prior to the boom. 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%. Calibrating θ^{pti} to match the corresponding front-end number for the Dodd-Frank requirements ($\theta^{pti} = 0.35$), generates largely similar effects, that can be found in the appendix.[32]

mortality") .

[30]The logit function is defined by

$$\operatorname{logit}(x) = \log(x) - \log(1-x).$$

[31]See e.g., Andersen et al. (2014), Keys et al. (2014).

[32]When adjusting between front-end and back-end ratios, I assume a constant 8% difference, matching

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 0.253, so that the steady state ratio of 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 (quarterly). 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.

For the housing adjustment parameter, I consider the special case $\zeta_h \to \infty$, so that the housing stocks are fixed. This simplifies the analysis, since house prices can now capture all movements in the housing market. 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.

To compute impulse responses I linearize around the steady state. For the credit liberalization experiments in Section 6, I compute deterministic transitions between steady states, under the assumption of a surprise change in parameters.

5 Results

This section uses numerical results to demonstrate the properties of the model, with particular focus on the novel features (PTI limits and endogenous prepayment). Section 5.1 demonstrates the effect of PTI limits in a simplified setting, while Section 5.2 shows the dynamics of the complete model and demonstrates the impact of endogenous prepayment on economic activity. For plots in the remainder of the paper, dashed lines will indicate economies with exogenous prepayment ($\rho_t = \bar{\rho}$), while solid lines will indicate economies with endogenous prepayment.

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 correspondence between a 28% front-end and 36% back-end ratio.

the effects of this credit limit structure, I consider the following three economies, which differ in their debt limits:

1. The **PTI Economy**: $\bar{m}_t = \bar{m}_t^{pti}$, so that the aggregate debt limit is exactly equal to the PTI limit.

2. The **LTV Economy**: $\bar{m}_t = \bar{m}_t^{ltv}$, so that the aggregate debt limit is exactly equal to the LTV limit.

3. The **Benchmark Economy**: $\bar{m}_t$ is defined as before using the debt limit (11).

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.[33] Figure 7 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.

These responses contain several results of interest. First, note that the PTI Economy displays a large debt response, with nearly twice the increase after 20Q relative to the LTV Economy (9.2% vs. 4.6%). This is due to the fact that PTI limits are themselves highly sensitive to interest rates, which directly enter the constraint. This can be seen in Figure 6a, which shows that the typical elasticity of PTI limits to interest rates is nearly 10. 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. Due to payments of principal, taxes, insurance, etc., the number is closer to 10%, but is still quite large.

Turning to the Benchmark Economy, we observe a substantial increase in debt following the shock. In fact the paths of debt, debt limits, and borrower expenditure in the Benchmark Economy are much closer to those of the PTI Economy than those of the LTV Economy. This may be somewhat surprising, since in the model, as is typically found in the empirical literature, a large majority of borrowers in the Benchmark Economy are constrained by LTV (72% in steady state).[34] While borrowers limited by PTI will have their constraints greatly expanded in the Benchmark Economy, this by itself is not enough to deliver the large aggregate response.

Instead, the key to this result lies in the interaction between the two constraints. This occurs through movements in $\mathcal{C}_t$, the collateral value of housing, which is in turn driven by changes in

[33] The required values are $\theta^{ltv} = 0.703$ and $\theta^{pti} = 0.192$, respectively.

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

F_t^{ltv}, the fraction of borrowers constrained by LTV. 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 7, 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.[35] 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, price-rent increase by up to 4% in the Benchmark Economy, far more than in either the LTV or PTI Economies, where these interaction effects are absent.[36]

This effect 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 still constrained by LTV find their borrowing limits relaxed following the fall in interest rates, leading to a much larger increase in overall credit growth observed. 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 8 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.

5.2 The Frontloading Effect

To complete the characterization of the mortgage credit channel, we can consider the effect of endogenous prepayment, the second main innovation of the model. In this section I demonstrate that endogenous prepayment dramatically changes the timing of credit issuance, which greatly increases transmission into economic activity. To see this, we can turn to Figure 9, which displays the response to a 1% technology shock that generates a fall in inflation and nominal interest rates. Similar to the exercise in Section 5.1, we can compare three alternative economies: the LTV and

[35] Figure 6d plots F_t^{ltv} as a function of PTI limits.

[36] The cause of the moderate rise in price-rent ratios in the LTV Economy is that borrowers actually prefer to borrow in low-inflation environments. The reason is that when nominal payments are constant, higher expected inflation actually means more frontloaded *real* payments. Impatient borrowers would prefer to delay payment further into the future, and thus prefer the flatter real payment schedule under low inflation. As a result, a fall in the inflation target increases the value of relaxing the borrowing limit μ_t, and therefore collateral value and house prices, since housing now allows borrowers to obtain a loan on more desirable terms.

Benchmark Economies with exogenous prepayment ($\rho_t = \bar{\rho}$), and a version of the Benchmark Economy with endogenous prepayment, so that ρ_t is determined by (32).

As can be seen in Figure 9, while under exogenous prepayment, the Benchmark Economy generates much larger rises in debt limits and house prices than the LTV Economy, and a larger increase in debt, these fail to translate into meaningful differences in output and inflation responses between the two specifications. This is due to the fact that in the model, as in the data, only a small minority of borrowers (around 4%) prepay their loans in a given quarter. In the exogenous prepayment economies, borrowers always prepay at this rate, and since debt limits only affect newly originated loans, a rise in debt limits translates into a very gradual increase in debt. As a result, most of the increase in borrower spending due to credit issuance occurs relatively far in the future, well after the majority of intermediate firms have reset their prices, which leads to a minimal effect on output.

Under endogenous prepayment however, borrowers react to the fall in interest rates by increasing prepayment rates. Low rates make prepayment more favorable for two reasons: the fixed interest rate on a new loan is lower, and, due to the impact of PTI limits described above, credit limits are higher, allowing for a larger loan. The annualized prepayment rate increases by nearly two percentage points, corresponding to a more than 10% increase in prepayments. As a result, borrower debt increases by much more in the endogenous prepayment version of the Benchmark Economy relative to its exogenous prepayment counterpart, despite the similar rise in debt limits between the two. Moreover, the increase in prepayments greatly expands the amount of credit being issued in the short run, before intermediate firms adjust their prices, generating substantial effects on output through the frontloading effect. In particular, output rises by 0.24% more on impact in the Benchmark Economy with endogenous prepayment, a 46% increase over the response in the exogenous prepayment models.

These results demonstrate that the prepayment option on fixed-rate mortgages can greatly amplify the real impact of shocks that affect long-term interest rates. This finding has direct policy relevance, for example providing theoretical underpinning for unconventional monetary policy that seeks to influencing the real economy through changes in long-term rates achieved using bond purchases.

6 Policy Implications

In this section, I apply the preceding results to two policy topics. Section 6.1 addresses the implications for monetary policy, while Section 6.2 considers the sources of the boom and bust, and the ramifications for macroprudential policy.

6.1 Monetary Policy

The first application considers the implications of the mortgage credit channel for the practice of monetary policy. While I have been assuming until now that the central bank follows the policy rule (24), the central bank is capable of perfectly stabilizing inflation in this model. While not as empirically realistic as (24), 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 (24) as $\psi_\pi \to \infty$, to obtain the alternative monetary policy equation (25), 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 10. 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 20% 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 10, 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, 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.

6.2 Credit Standards and Macroprudential Policy

In this section, I consider the implications of the model for the sources of the 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 price-rent ratios (using implied rents, this is $p_t^h/(u_{b,t}^h/u_{b,t}^c)$) and debt-to-household income ratios (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.[37]

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

[37]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).

have typically focused on changes in LTV standards as the cause.[38] In a world with only LTV limits, this would indeed be possible, as confirmed by Figure 11. This figure 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.[39] The result is a large rise in debt, house prices, and price-rent ratios — exactly what was observed during the boom — confirming the findings of these papers. One result of note is that while the maximum LTV ratio is relaxed by 14%, debt eventually rises by nearly twice that level. This is due to a further *endogenous* relaxation of LTV limits due to the contemporaneous rise in house prices.

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 2.3, what is the impact of a relaxation of PTI standards themselves? To answer these questions, Figure 12 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.[40] These experiments produce strikingly different results. To answer the first question above, incorporating PTI limits severely dampens the impact of an LTV liberalization. Unlike the results in Figure 11, liberalizing LTV standards in the Benchmark Economy creates a small rise in debt (17% of observed increase in debt-to-household-income) and actually causes house prices to *fall* (-3.4% of observed increase in price-rent ratios). This experiment implies that even a near-complete liberalization of LTV ratios is unable to generate a large boom when PTI limits are maintained at historical limits.

What explains this disparity? Incorporating PTI limits has a direct effect on credit growth by limiting the amount by which overall credit limits are relaxed. But the addition of PTI limits also has important general equilibrium effects. As LTV standards are loosened, more borrowers find themselves constrained by PTI, as shown by the fall in F_t^{ltv} by more than 10 percentage points

[38] An important exception is Justiniano et al. (2015a), who focus on constraints on lending supply alongside LTV constraints.

[39] Specifically, maximum LTV ratios are changed from 70% to 80% and then restored to 70%. The low initial value (70%) is used to match the overall credit limit in the Benchmark Economy.

[40] 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 refers to a front-end ratio (implying $\theta^{pti} = 0.5$) or back-end ratio ($\theta^{pti} \simeq 0.42$), I choose the intermediate value of $\theta^{pti} = 0.46$.

in Figure 12. 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.

For the answer to the second question, and in stark contrast to the previous findings, the relaxation of PTI standards generates a large boom in debt and house prices, accounting for 43% of the increase price-rent ratios and 53% 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 roughly 20 percentage points at the peak. 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 $(0.85, 0.28)$ to $(0.99, 0.46)$ and then unexpectedly returning them to their initial values after 32 quarters can be found in Figure 13. This path generates a larger increase in debt (92% 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.[41] In this section, I examine this policy choice, and affirm that a cap on PTI ratios, not LTV ratios, is the more effective macroprudential policy for limiting the amplitude of boom-bust cycles.

This conclusion follows naturally from the above results, which show that a fixed PTI limit can prevent a boom caused by the relaxation of LTV standards, but that the converse is not true: 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 14, in which LTV and PTI are both liberalized, but θ^{pti} is only allowed to rise to the Dodd-Frank limit, which I calibrate to 35%.[42] 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. To demonstrate this phenomenon, I run a final transition path, shown in Figure 15, 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 Economy, PTI limits keep the boom-bust cycle in check. Once again this is due to the constraint switching effect: as houses become more valuable, LTV constraints loosen, and more borrowers find themselves constrained by PTI, dampening the rise in house prices and debt. This result further indicates that, while factors besides credit standards likely played an important role in the boom-bust, their ability to do so may have hinged on PTI limits being relaxed beyond historical levels.

In summary, these experiments offer a valuable insight about macroprudential policy. If a primary aim of such a policy is to dampen the rise in debt and house prices during booms that are caused or exacerbated by credit liberalization, then a PTI limit appears to be a more effective tool than an LTV limit. This finding largely validates the choice of policymakers in focusing on PTI rather than LTV when crafting underwriting standards for Qualified Mortgages in the Dodd-Frank reforms.

[41] Technically speaking, 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.

[42] The disparity between this number and 43% is due to the fact that the Dodd-Frank limit is on "back-end" PTI ratios, while my model expresses PTI limits in terms of "front-end" ratios.

7 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 the as $\phi_z \to 1$ we have $dC_t \to 0$ for all t. Impacts for intermediate values of ϕ_z are displayed in Figure 16, which reveal that for $\phi_z = 0.992$, the persistence associated with the duration of a 30-year mortgage, the net impact has been cut by nearly 60% due to an offsetting response by the saver. 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

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

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 17. 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.[43]

8 Conclusion

In this paper, I have studied the role of mortgage markets in macroeconomic transmission, focusing on the mortgage credit channel: the path from primitive shocks, to interest rates, through mortgage credit growth, into the rest of the macroeconomy. The modeling framework I construct contains a realistic mortgage structure with several novel elements, including tractable methods for aggregating over PTI and LTV limits that may bind separately for heterogeneous borrowers, and allowing for infrequent but endogenous prepayment of fixed-rate mortgages. Incorporating these features has profound effects on macroeconomic dynamics, with the benchmark model displaying much greater larger responses of credit growth to movements in interest rates, relative to models without PTI limits or endogenous prepayment. Moreover, the interactions between the LTV and PTI limits generate a new channel through which movements in interest rates influence house prices that would not be present under either constraint alone, and appears to have also

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

been critical for the recent housing boom. Because credit growth increases borrower demand without a large offsetting decrease in saver demand, these changes in credit growth can transmit strongly into changes in output and inflation when monetary policy is not too responsive.

These findings have important implications for policy. First, I showed that the mortgage credit channel helps the central bank with stabilization, requiring smaller movements in the policy rate to return inflation to target following a shock, relative to an alternative model with no PTI limit and exogenous prepayment. However, these smaller movements are associated with larger movements in credit growth, creating a potential dilemma for policymakers. Finally, the model revealed that relaxation of PTI limits can explain most of the rise in debt and price-rent ratios during the boom, and that a macroprudential cap on PTI limits would have greatly dampened the amplitude of the boom and bust.

This paper 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 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 led to a large increases 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.

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Tables and Figures

Parameter	Name	Value	Internal	Target/Source
Saver discount factor	β_s	0.993	Y	Real rate = 3%
Borrower discount factor	β_b	0.95	N	
Fraction of borrowers	χ_b	0.35	N	2001 SCF (see text)
Prepay rate	ρ	0.045	N	Avg. FRM prepayment 1994-2015
Issuance cost mean	μ_κ	0.188	Y	Average prepayment rate
Issuance cost scale	s_κ	0.0330	Y	See text
Income dispersion	σ_e	0.411	N	Fannie Mae
Borr. housing preference	ξ	0.253	Y	$h_b/w_b n_b = 8.68$ (2001 SCF)
Steady state inflation	π^{ss}	1.0075	N	Avg. infl. = 3%
Variety elasticity	λ	6.0	N	
Inv. Frisch Elasticity	φ	1.0	N	
Disutility of Labor	η	7.935	Y	$n = 1/3$
Price stickiness	ζ	0.75	N	
Mortgage amortization	ν	1/120	N	30-year duration
Taylor rule (inflation)	ψ_π	1.5	N	
Taylor rule (output)	ψ_y	0	N	
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)
TFP (pers.)	ϕ_a	0.9641	N	Garriga et al. (2015)
TFP (std.)	σ_a	0.0082	N	Garriga et al. (2015)
Credit limits (pers.)	ϕ_θ	0.9	N	
Max PTI Ratio	θ^{pti}	0.28	N	
Max LTV Ratio	θ^{ltv}	0.85	N	
PTI Ratio Offset	τ	0.0375 / 4	N	
Housing adj. cost	ζ_h	∞	N	Fixed housing stock

Table 1: Parameter Values: Baseline Calibration

Notes: FRM prepayment rates are computed for loans securitized by Fannie Mae, Freddie Mac, and Ginnie Mae only, and do not include non-agency loans (source: eMBS).

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

Table 2: Prepayment Regression

Notes: results are from a logistic regression computing (40). 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.

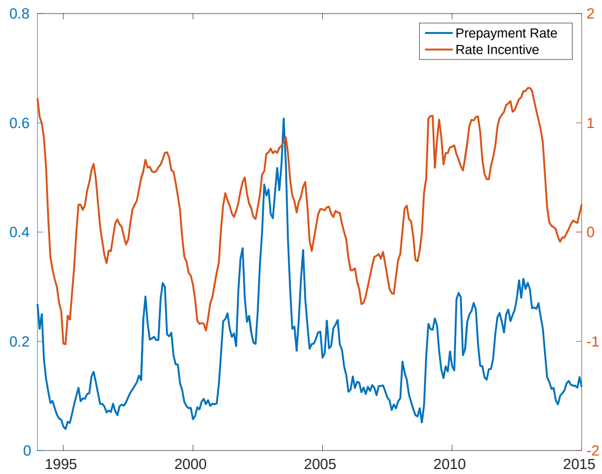


Figure 1: Prepayment Rate vs. Interest Rate Incentive

Notes: "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.

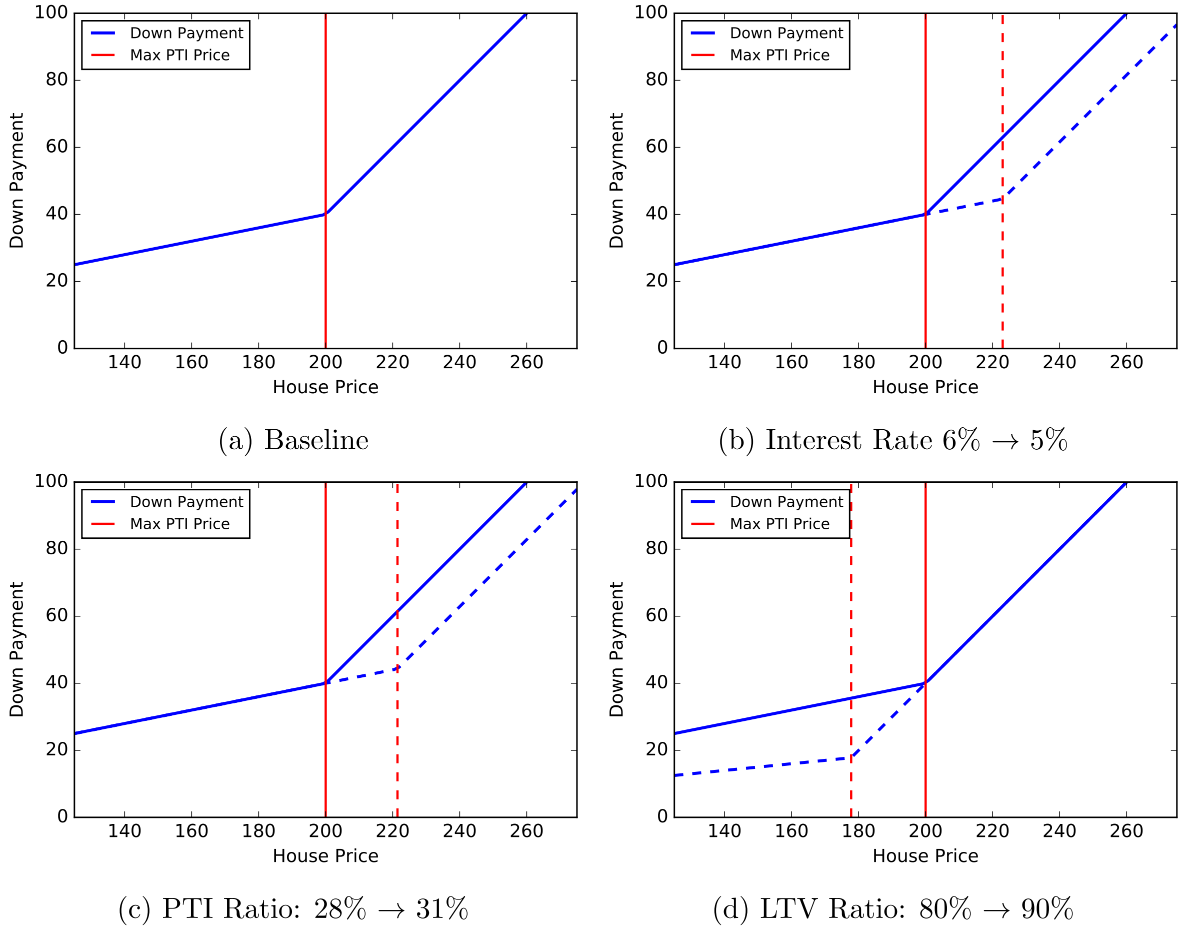
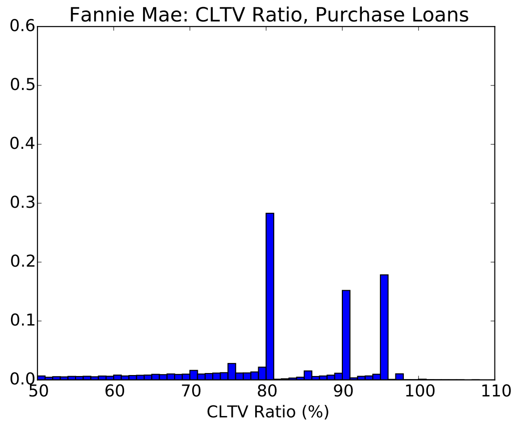
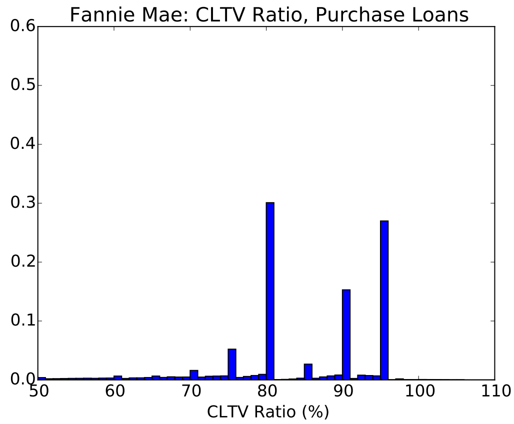


Figure 2: Simple Example: House Price vs. Down Payment

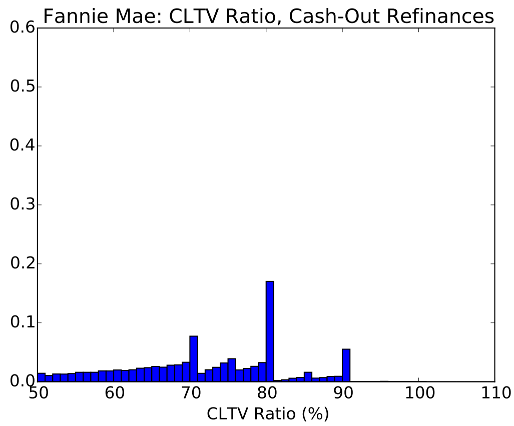
Notes: Plots correspond to the borrower's choice sets in Section 2.2.



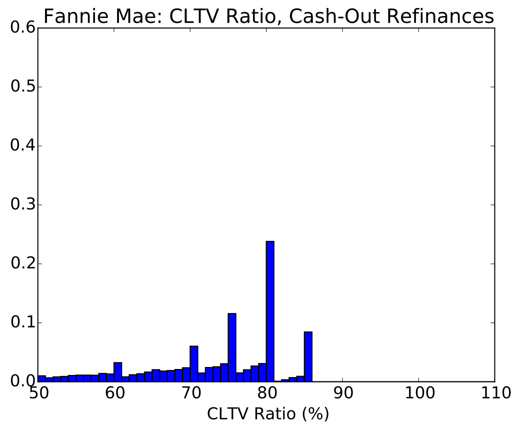
(a) CLTV of Purchase Loans (2006 Q1)



(b) CLTV of Purchase Loans (2014 Q3)



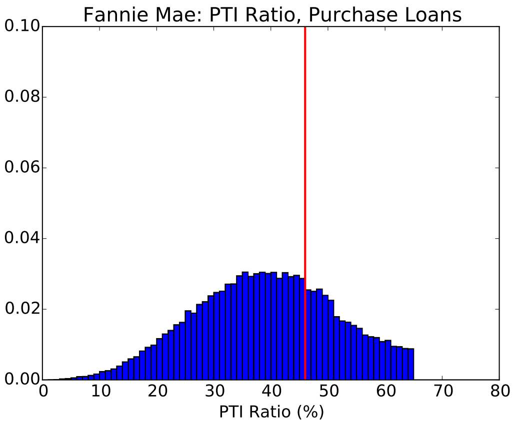
(c) CLTV of Cash-Out Refinances (2006 Q1)



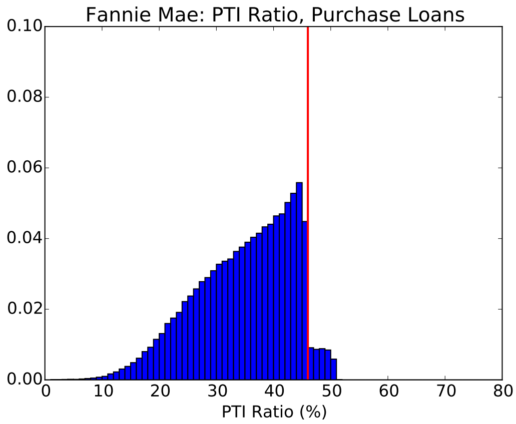
(d) CLTV of Cash-Out Refinances (2014 Q3)

Figure 3: Fannie Mae: CLTV on Newly Originated Mortgages

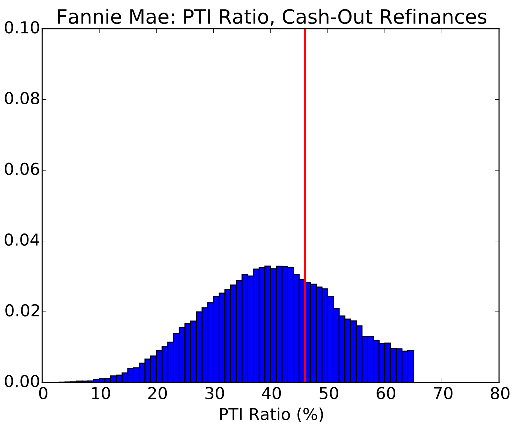
Source: Fannie Mae Single Family Dataset, issuance data. Histograms are weighted by loan balance.



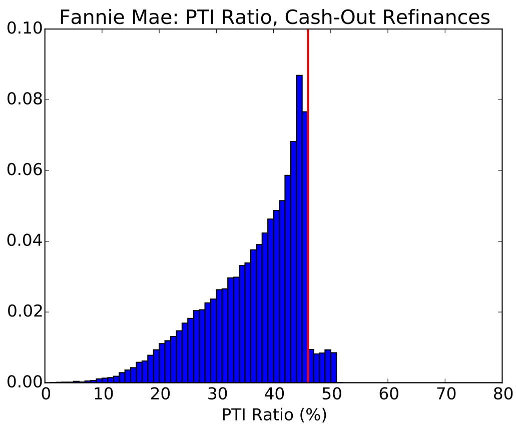
(a) PTI of Purchase Loans (2006 Q1)



(b) PTI of Purchase Loans (2014 Q3)



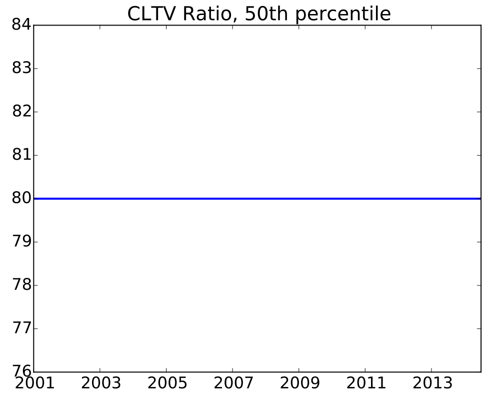
(c) PTI of Cash-Out Refinances (2006 Q1)



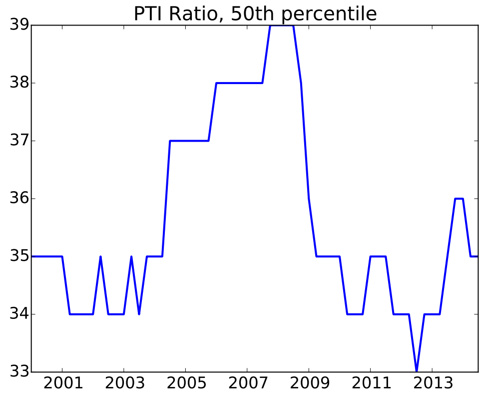
(d) PTI of Cash-Out Refinances (2014 Q3)

Figure 4: Fannie Mae: PTI on Newly Originated Mortgages

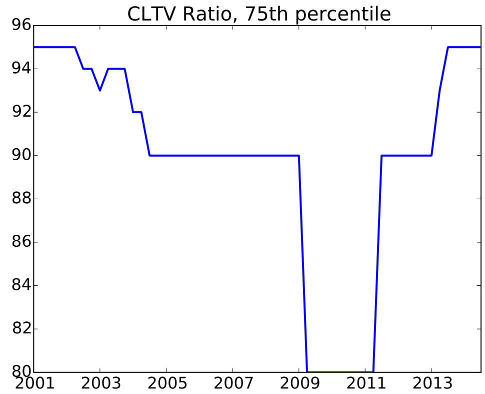
Source: Fannie Mae Single Family Dataset, issuance data. Histograms are weighted by loan balance.



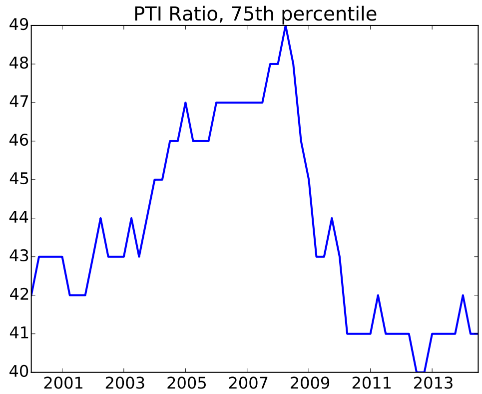
(a) CLTV: 50th Percentile



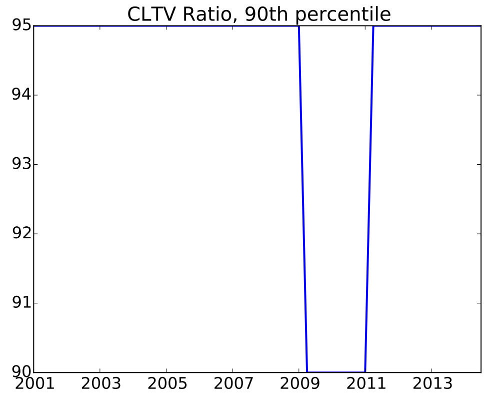
(b) PTI: 50th Percentile



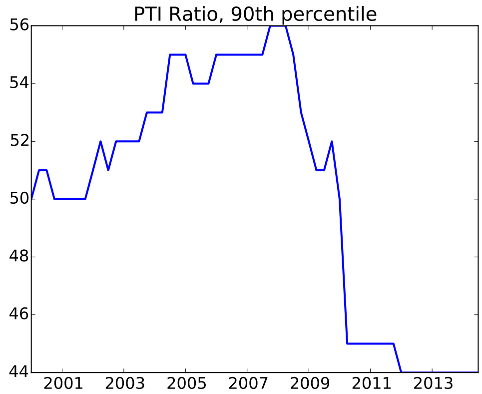
(c) CLTV: 75th Percentile



(d) PTI: 75th Percentile



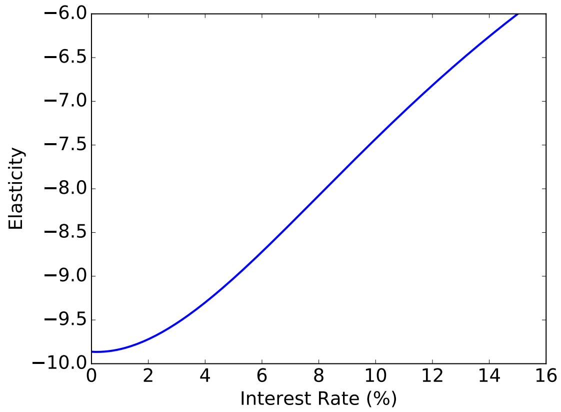
(e) CLTV: 90th Percentile



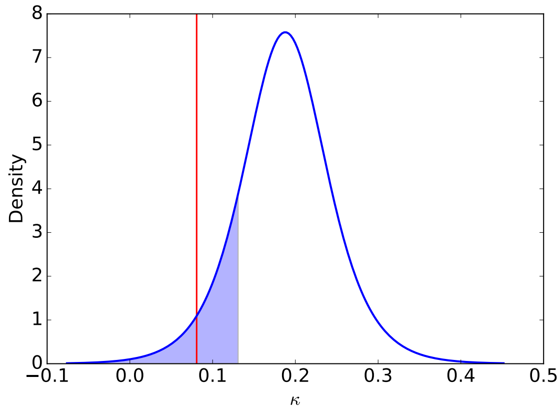
(f) PTI: 90th Percentile

Figure 5: Fannie Mae: CLTV and PTI Percentiles for Newly Originated Purchase Mortgages

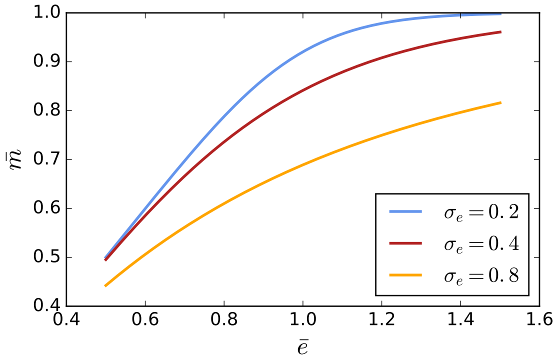
Source: Fannie Mae Single Family Dataset, issuance data.



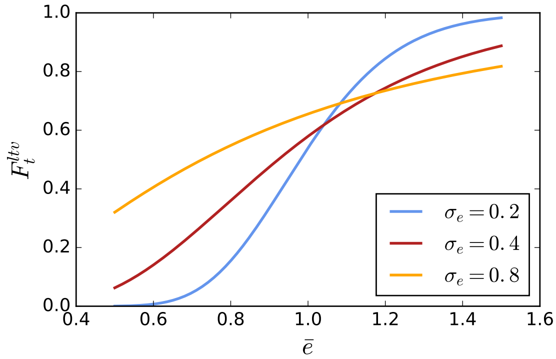
(a) Elasticity of PTI Limit to Rate



(b) Cost Distribution



(c) Overall Limit



(d) Frac. Limited by LTV

Figure 6: Model Functional Forms

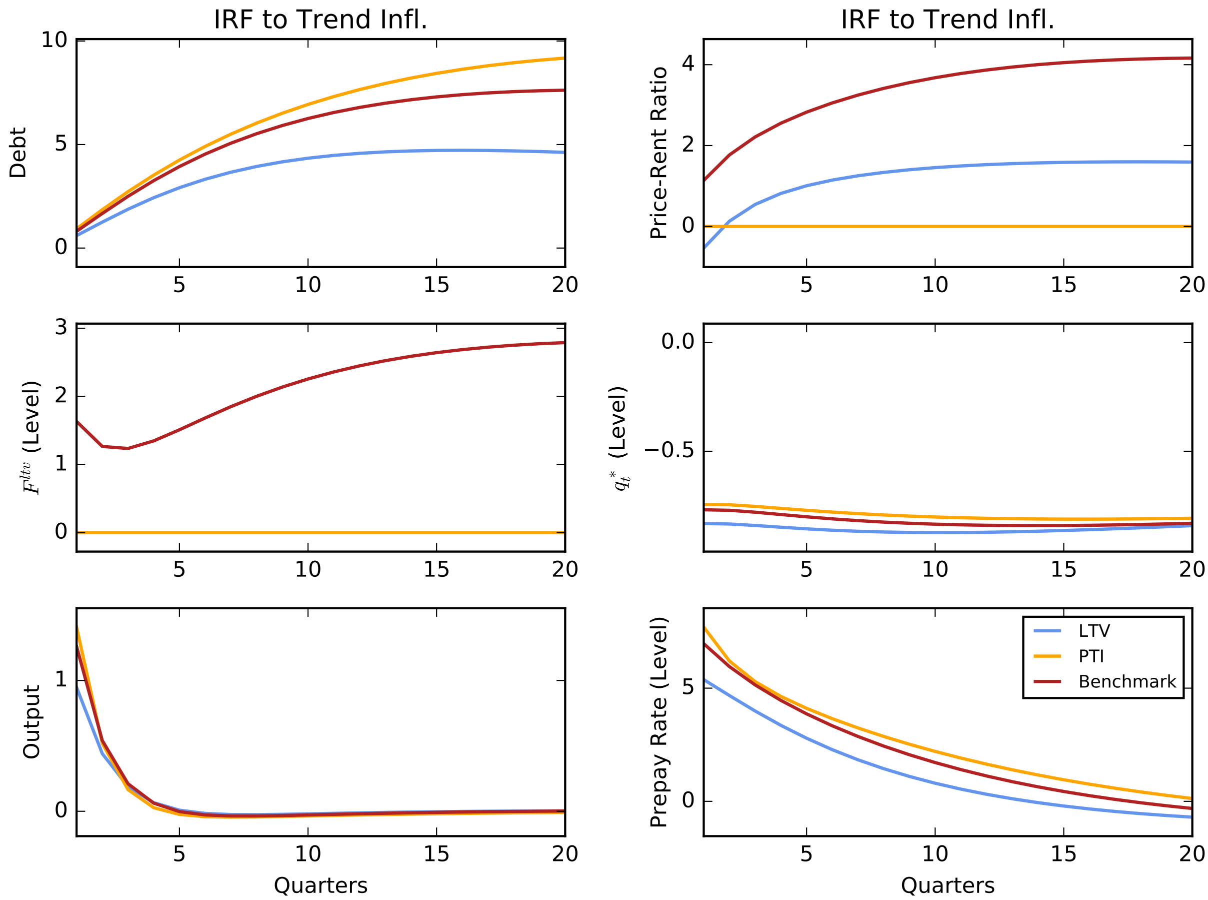


Figure 7: Impulse Response to -1% (Annualized) Trend Inflation Shock: Comparison of LTV, PTI, Benchmark Economies

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels."Price-Rent Ratio" is the "price-rent" ratio $p_t^h/(u_{b,t}^h/u_{b,t}^c)$. q_t^* (Level) is the coupon rate on a new mortgage. "Output" is output. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%).

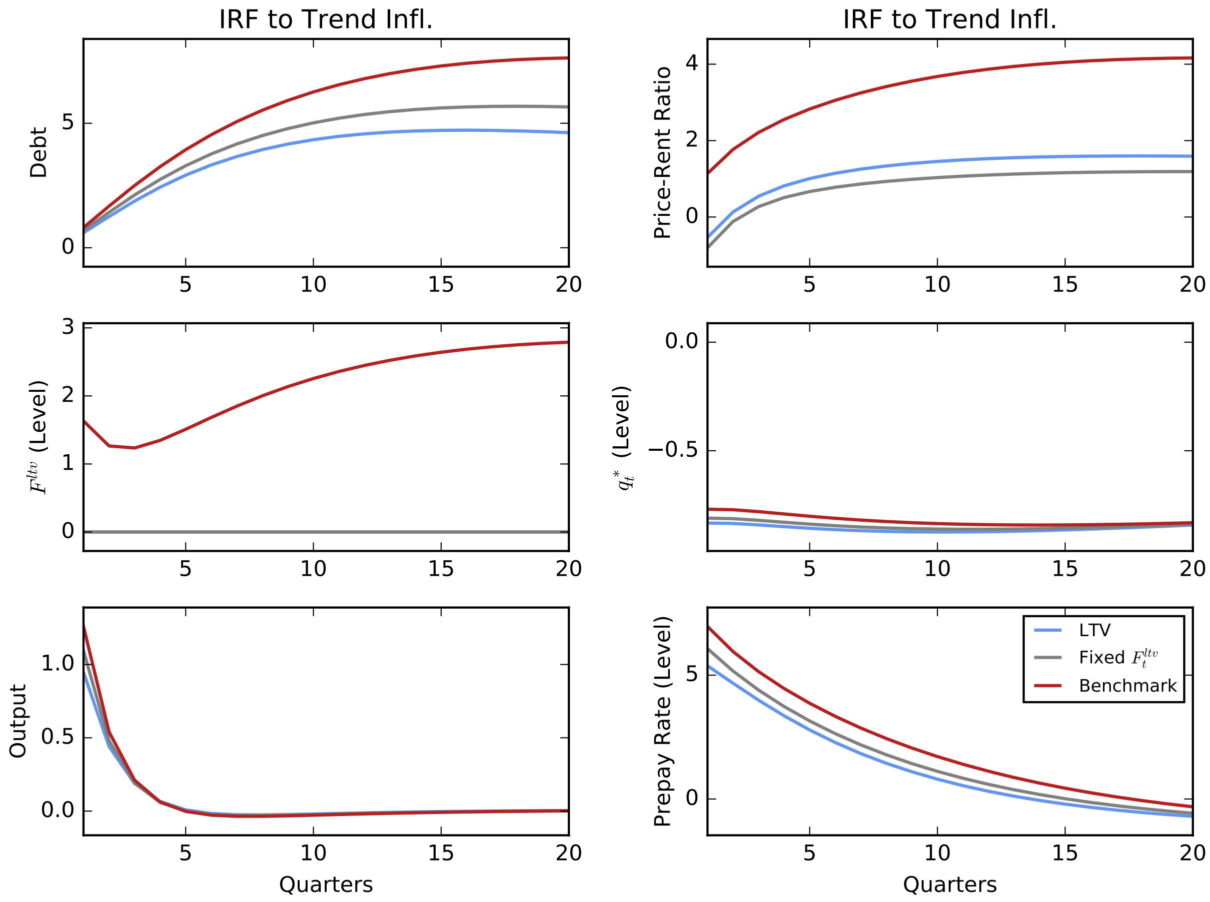


Figure 8: Impulse Response to -1% (Annualized) Trend Inflation Shock: Comparison of LTV, Benchmark, and Fixed F_t^{ltv} Economies

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels."Price-Rent Ratio" is the "price-rent" ratio $p_t^h/(u_{b,t}^h/u_{b,t}^c)$. q_t^* (Level) is the coupon rate on a new mortgage. "Output" is output. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%).

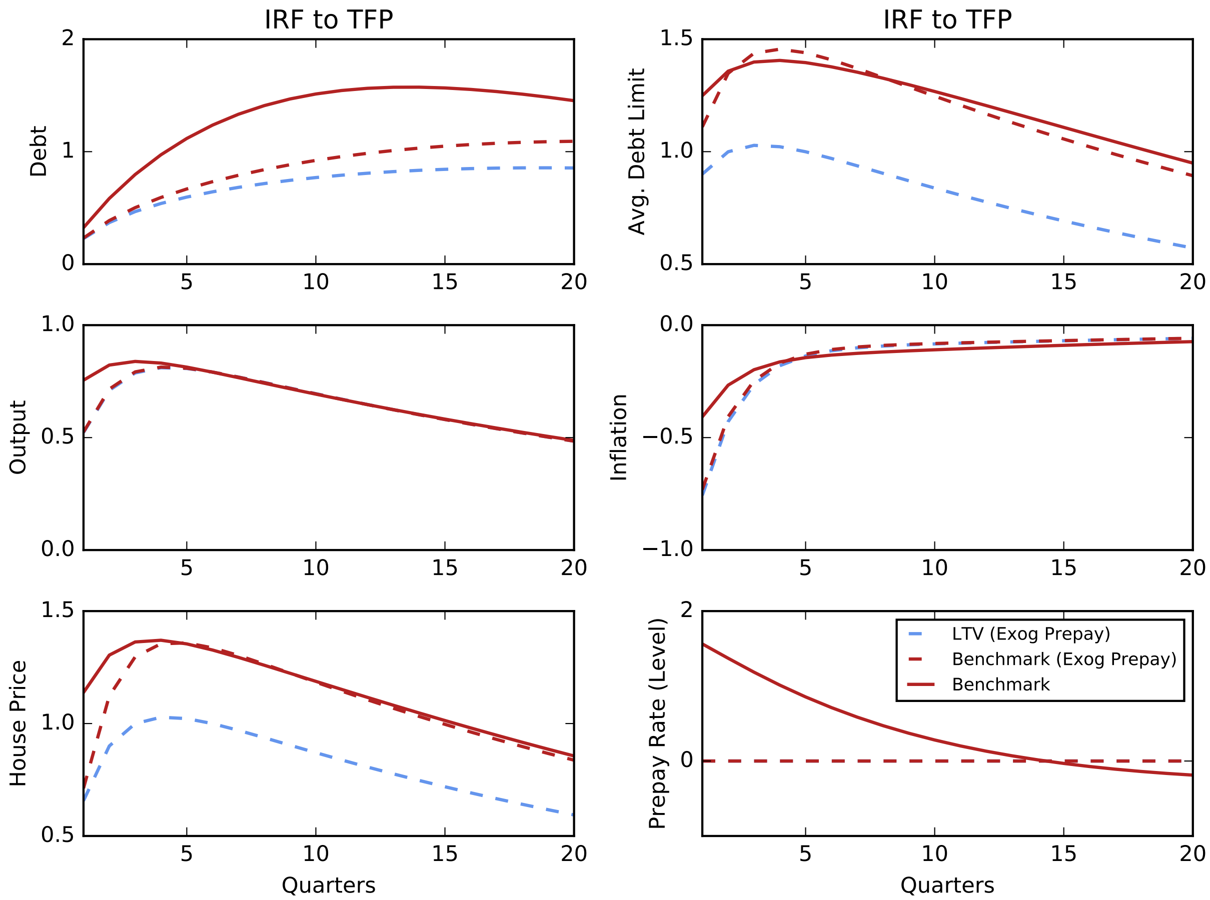


Figure 9: Impulse Response to 1% Technology Shock: Comparison of LTV (Exogenous Prepayment), Benchmark (Exogenous Prepayment), and Benchmark (Endogenous Prepayment) Economies, Smoothed Policy Rule

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels. "Avg Debt Limit" is the total credit limit $\bar{m}_t$. "Output" is output. "House Price" is house price. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%).

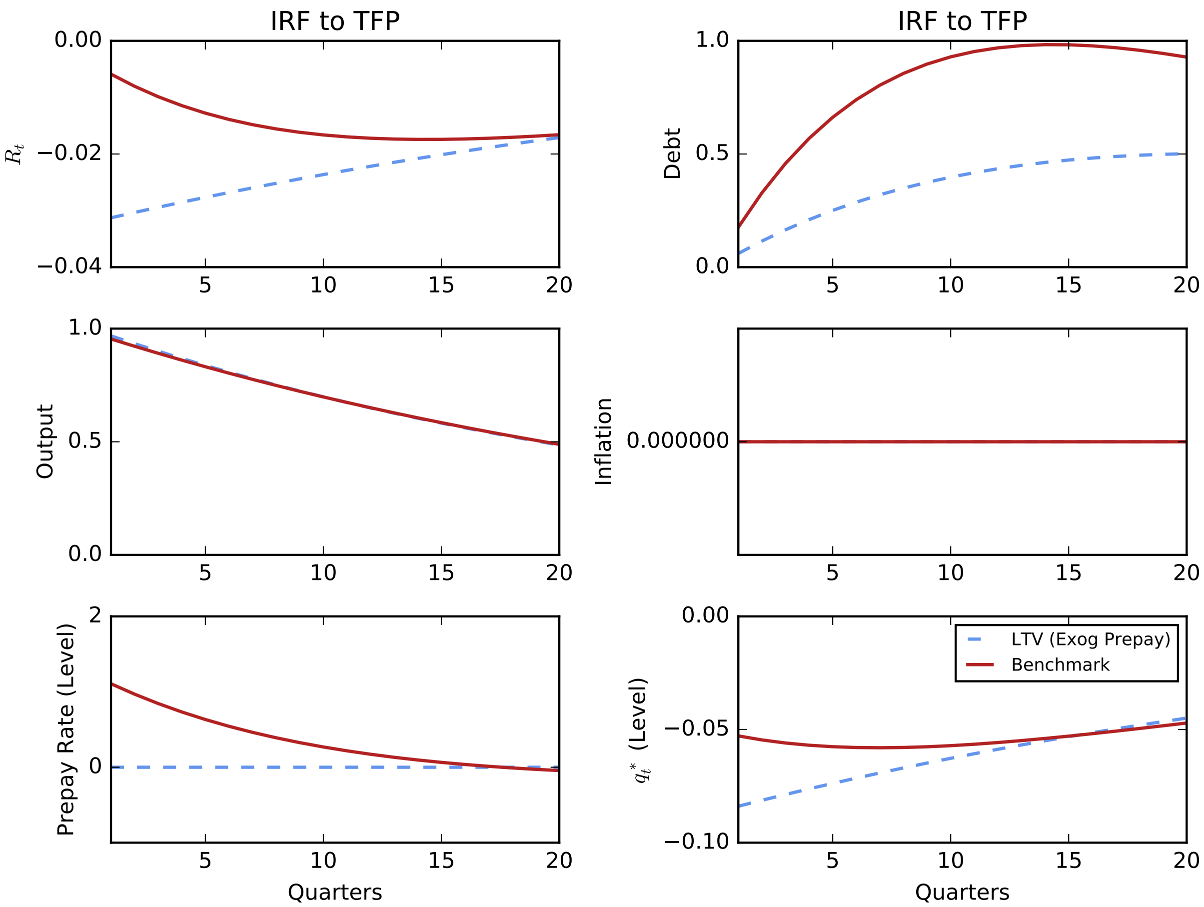


Figure 10: Impulse Response to 1% TFP Shock: Comparison of LTV (Exogenous Prepayment) and Benchmark (Exogenous Prepayment) Economies, Perfect Inflation Stabilization

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels. R_t is risk-free nominal rate. "Output" is output. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%). q_t^* (Level) is the coupon rate on a new mortgage.

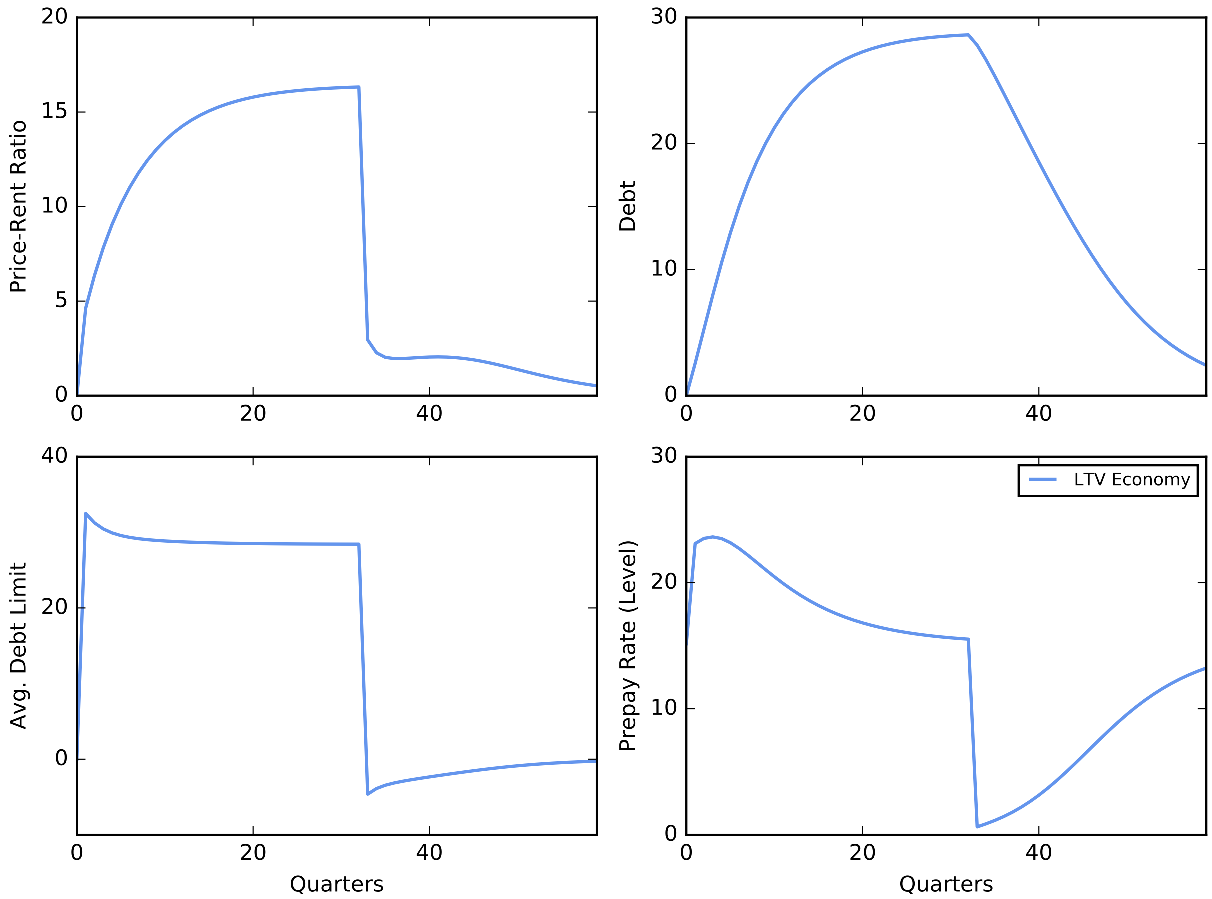


Figure 11: Credit Loosening Experiment: LTV Economy

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels. "Price-Rent Ratio" is the "price-rent" ratio $p^h_t/(u^h_{b,t}/u^c_{b,t})$. "Avg Debt Limit" is the total credit limit $\bar{m}_t$. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%). 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%.

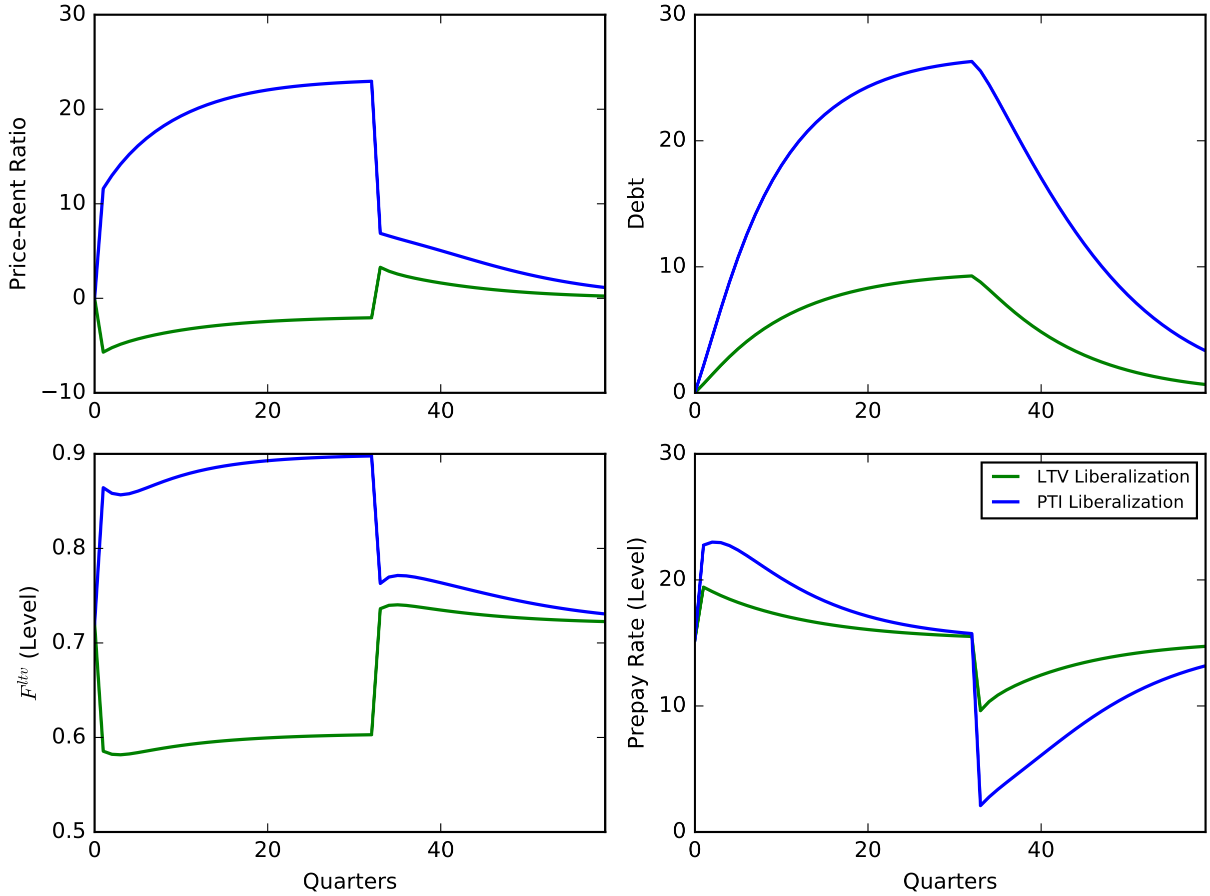


Figure 12: Credit Loosening Experiment: LTV Liberalization vs. PTI Liberalization

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels. "Price-Rent Ratio" is the "price-rent" ratio $p_t^h/(u_{b,t}^h/u_{b,t}^c)$. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%). For the path "LTV Only": at time zero, the LTV limit θ^{ltv} is unexpectedly loosened from 85% to 99%, and after 32Q, is unexpectedly tightened from 99% to 85%. For the path "PTI Only": at time zero, the PTI limit θ^{pti} is unexpectedly loosened from 28% to 46%, and after 32Q, is unexpectedly tightened from 46% to 28%.

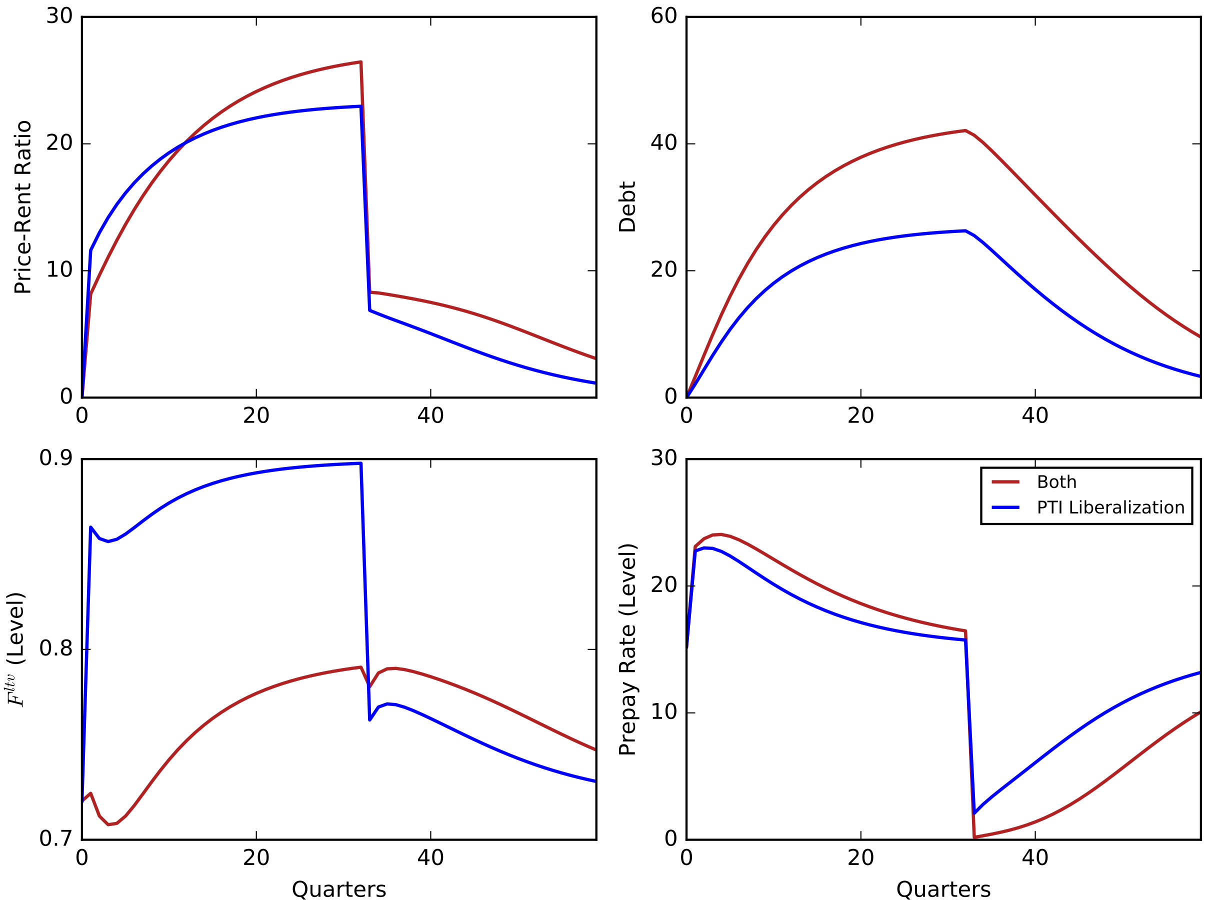


Figure 13: Credit Loosening Experiment: Full Liberalization vs. PTI Liberalization Only

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels. "Price-Rent Ratio" is the "price-rent" ratio $p_t^h/(u_{b,t}^h/u_{b,t}^c)$. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%). For the path "Both": at time zero, the LTV limit θ^{ltv} and PTI limit θ^{pti} are both unexpectedly loosened from (85%, 28%) to (99%, 46%), and after 32Q, is unexpectedly tightened from (99%, 46%) to (85%, 28%). For the path "PTI Only": at time zero, the PTI limit θ^{pti} is unexpectedly loosened from 28% to 46%, and after 32Q, is unexpectedly tightened from 46% to 28%.

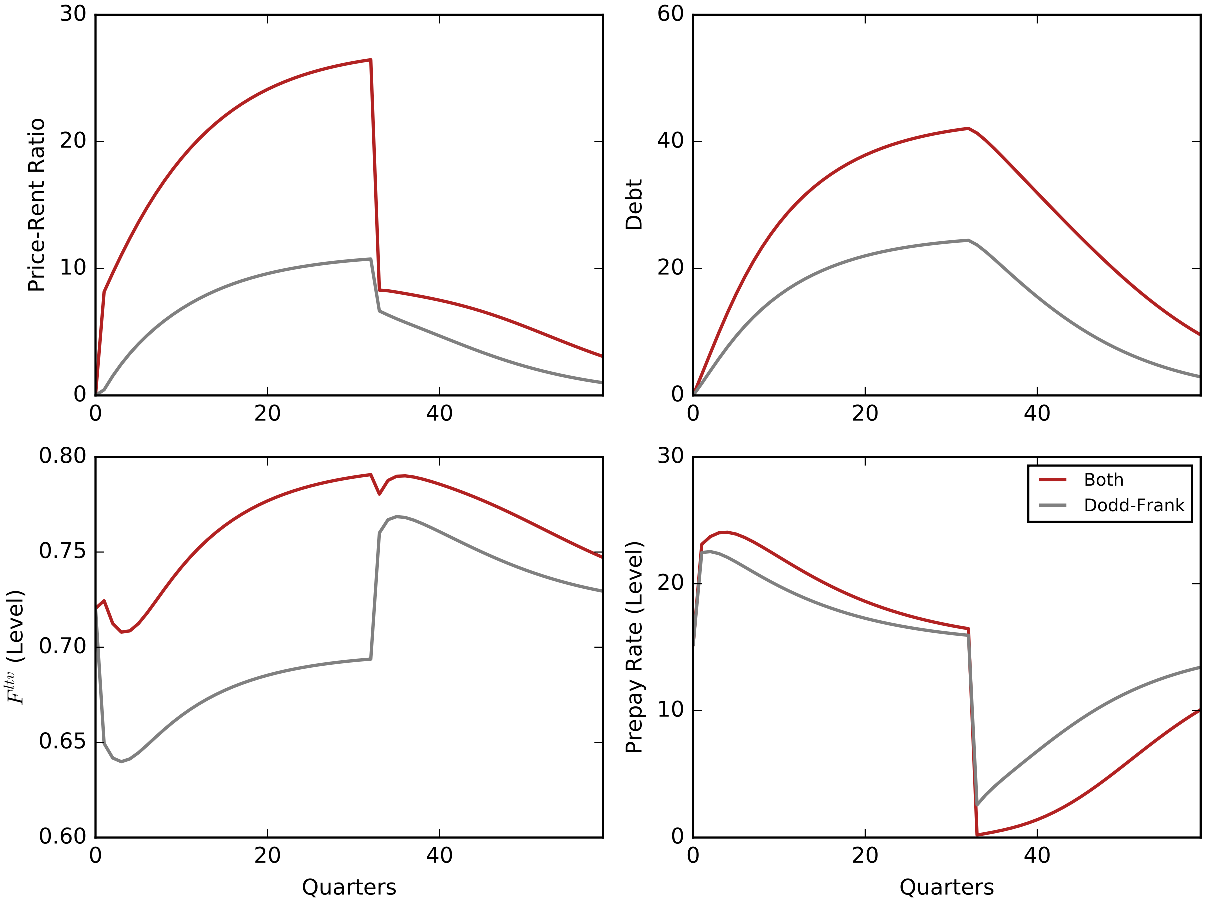


Figure 14: Credit Loosening Experiment: Full Liberalization vs. Approximate Dodd-Frank Limit

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels. "Price-Rent Ratio" is the "price-rent" ratio $p_t^h/(u_{b,t}^h/u_{b,t}^c)$. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%). For the path "Both": at time zero, the LTV limit θ^{ltv} and PTI limit θ^{pti} are both unexpectedly loosened from (85%, 28%) to (99%, 46%), and after 32Q, is unexpectedly tightened from (99%, 46%) to (85%, 28%). For the path "Dodd-Frank": at time zero, the LTV limit θ^{ltv} and PTI limit θ^{pti} are both unexpectedly loosened from (85%, 28%) to (99%, 35%), and after 32Q, is unexpectedly tightened from (99%, 35%) to (85%, 28%).

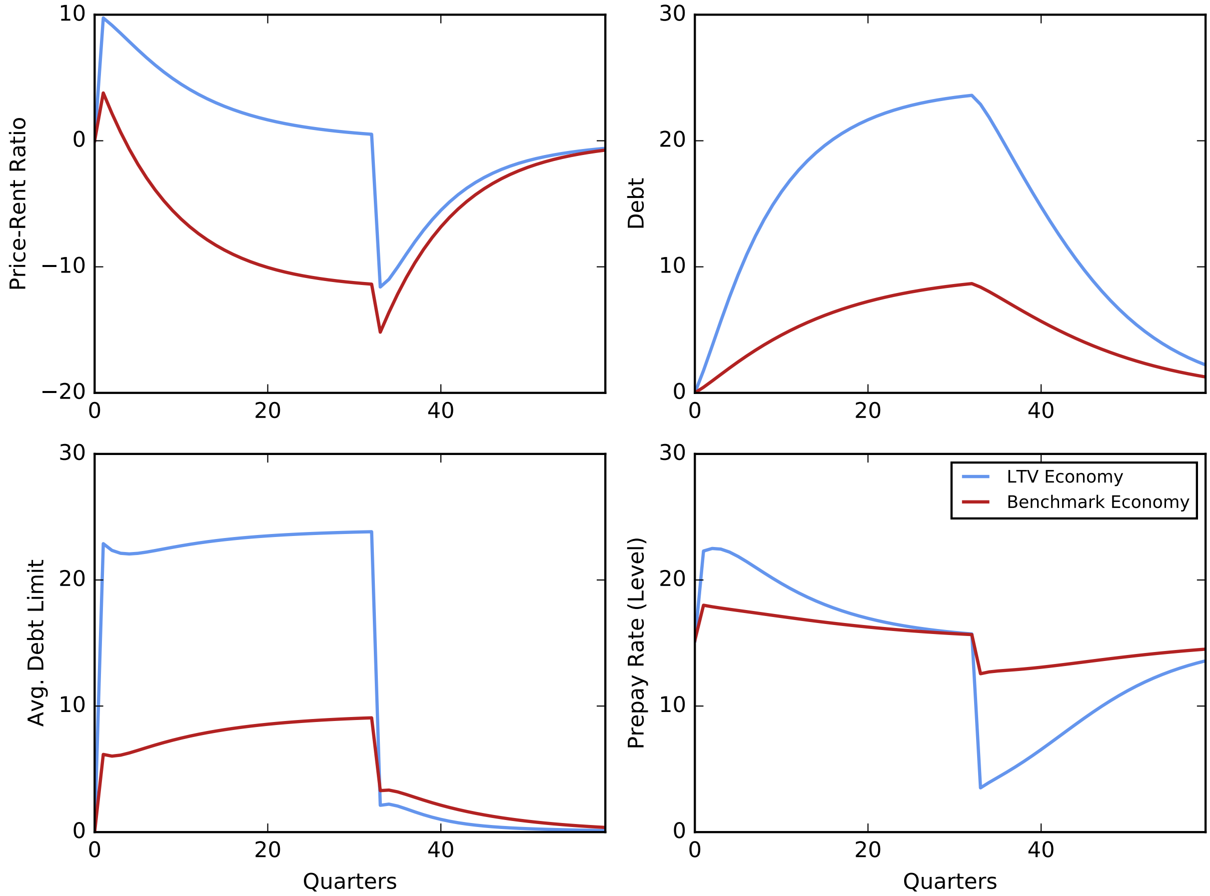


Figure 15: Housing Preference Experiment: LTV Economy vs. PTI Economy

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels."Price-Rent Ratio" is the "price-rent" ratio $p_t^h/(u_{b,t}^h/u_{b,t}^c)$. "Avg Debt Limit" is the total credit limit $\bar{m}_t$. "Prepay Rate (Level)" is the annualized conditional prepayment rate (CPR) in percent (minimum 0%, maximum 100%). 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.

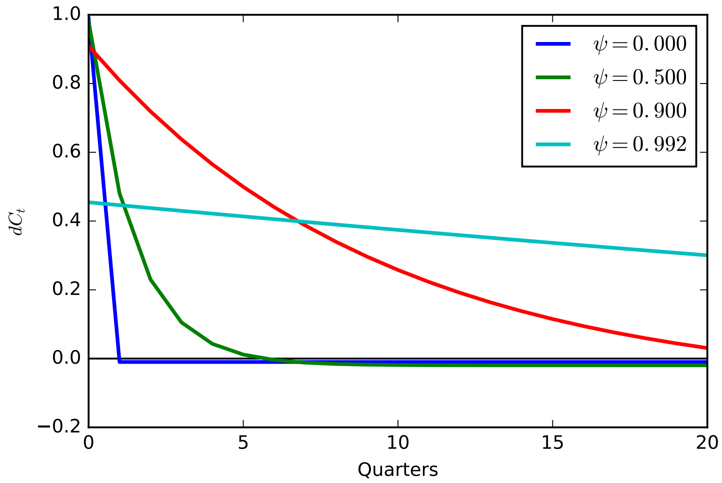


Figure 16: Effect of Redistribution on Aggregate Consumption (Partial Equilibrium)

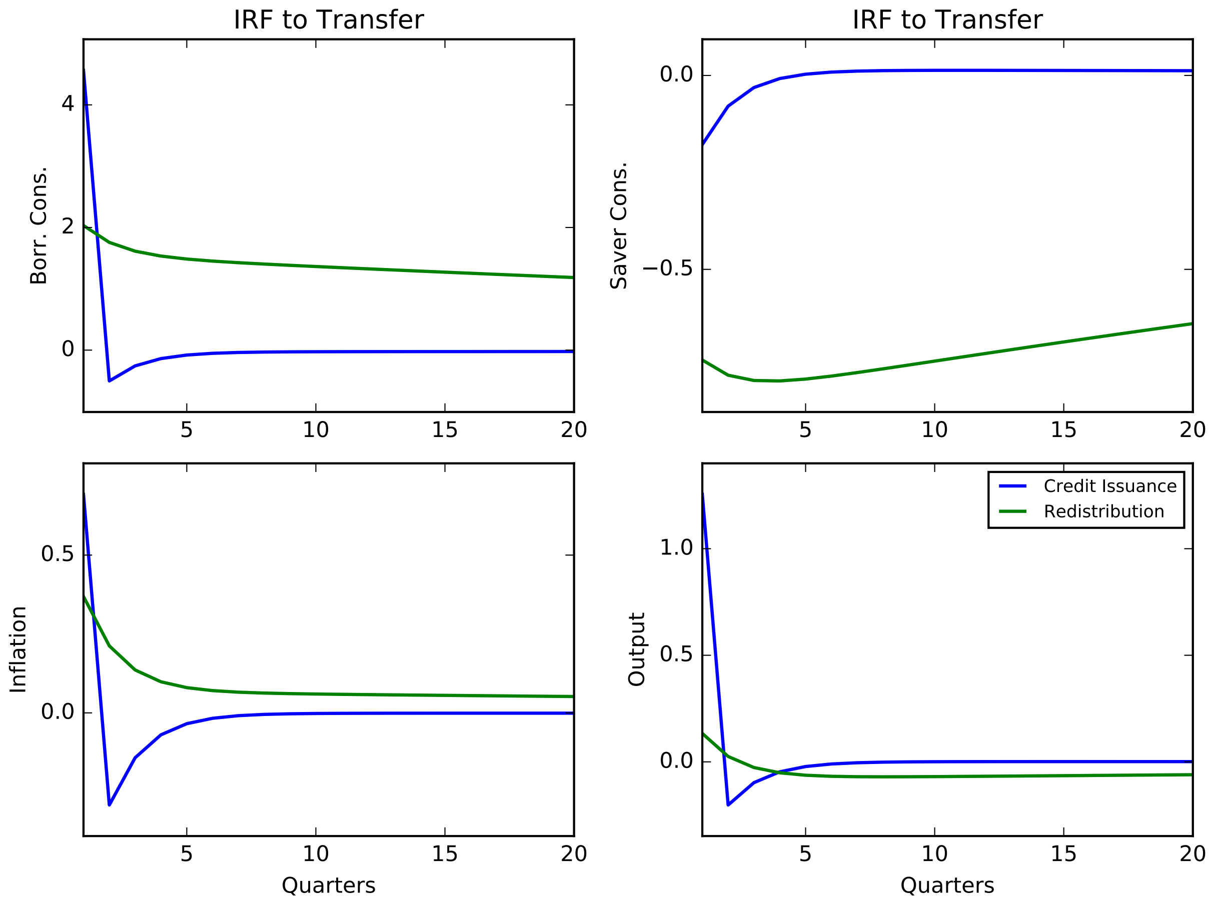


Figure 17: Impulse Response to 1% Credit Issuance, Redistribution Shocks (Simple Model).

Notes: All variables without the note "(Level)" are expressed in deviations from steady state, so that e.g., a value of 1 represents a 1% increase relative to steady state. Variables with the note "(Level)" are expressed as deviations from steady state in levels."Borr Cons" is borrower nondurable consumption. "Saver Cons" is saver nondurable consumption. "Output" is output.