Multiple Credit Constraints and Time-Varying Macroeconomic Dynamics

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Abstract

Macroeconomic models generally predict linear responses to house price and credit shocks, contrary to the predictions of non-linear VAR models. Motivated by this, I build a model with two occasionally binding credit constraints: a loan-to-value (LTV) constraint and a debt-service-to-income (DTI) constraint. The implied dynamics are highly non-linear, and differ radically from models with only an occasionally binding LTV constraint. A Bayesian estimation of the model infers when the constraints have been binding during 1975-2017, and which shocks that caused them to bind. A macroprudential experiment shows that countercyclical LTV limits cannot dampen mortgage debt growth in expansions, but DTI limits can.

JEL classification: C32, D58, E32, E44.

Keywords: Threshold VAR model. Loan-to-value constraint. Debt-service-to-income constraint. Non-linear estimation of DSGE models.

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1 Introduction

The analysis starts by documenting a significant state-dependency in the real response to house price and mortgage credit shocks. Using a threshold VAR model, I estimate the correlations between consumption, mortgage credit, and house prices on U.S. data. Positive shocks to the house price or mortgage credit always cause all three variables to increase. However, for house price shocks, the responses of consumption and mortgage credit are twice as large when the house price (the threshold variable) is low, compared to when it is high. Similarly, for mortgage credit shocks, the responses of consumption and house prices are significantly larger and more persistent when the house price is low, compared to when it is high. This new evidence comes in addition to a growing literature on credit spread shocks, which shows that these shocks have highly asymmetric (i.e., adverse shocks have larger effects than favorable shocks) and state-dependent (i.e., shocks have larger effects in contractions than in expansions) effects on real activity.[1]

While strong empirical evidence on non-linear effects of house price and credit shocks exists, macroeconomic models remain silent on the causes of these non-linearities. State-of-the-art models, such as Guerrieri and Iacoviello (2017), Jensen, Ravn, and Santoro (2018), and Jensen, Petrella, Ravn, and Santoro (2017), with occasionally binding loan-to-value constraints do capture some non-linearity following *large positive* shocks that unbind this constraint. However, the reactions of these models to housing preference and credit shock are symmetric up until the point where the loan-to-value constraint unbinds. For realistic calibrations of the models, this unbinding typically does not occur for small- and medium-sized shocks or for negative shocks that tighten the constraint.

I explain the non-linear effects of house price and credit shocks in a novel real business cycle model with two occasionally binding credit constraints: a loan-to-value (LTV) constraint and a debt-service-to-income (DTI) constraint. With this setup, homeowners must fulfill a collateral requirement and a debt service requirement in order to qualify for a mortgage loan.[2] The DTI constraint is a generalization of the natural borrowing limit in Aiyagari (1994). The LTV constraint is the solution to a debt enforcement problem, as in Kiyotaki and Moore (1997). The resulting model features highly asymmetric and state-dependent dynamics. These nonlinearities arise either because both constraints unbind or (much more frequently) because of switching between which of the constraints that binds. By contrast, models with only an occasionally binding LTV constraint can-

[1] See, e.g., Hubrich and Tetlow (2015), Barnichon et al. (2017), and Prieto et al. (2016).

[2] Greenwald (2018) shows that borrowers bunch around institutional DTI limits, in addition to bunching around institutional LTV limits.

not reproduce these nonlinear dynamics since their constraint does not unbind regularly, essentially leaving these models linear.[3]

The credit constraints together predict that only if both house prices and labor incomes increase, may homeowners take on additional debt. I test this prediction by estimating the elasticities of mortgage loan origination with respect to house prices and personal incomes on U.S. county-level panel data covering 2008-2016. I find that both elasticities are highly state-dependent. The elasticity with respect to house prices is zero when incomes are not growing and 0.48 when they are. Similarly, the elasticity with respect to incomes is zero when house prices are not growing and 0.41 when they are. These estimates are among the first in an otherwise large micro-data literature to suggest that the effects of house price and income growth on equity extraction are state-dependent.

I estimate the model by Bayesian maximum likelihood on time-series covering the U.S. economy in 1975-2017. I use the approach in Guerrieri and Iacoviello (2017) in order to handle the non-linearities, which the occasionally binding constraints introduce. The estimation identifies when the respective two credit constraints have been binding and which shocks that caused them to bind. At least one credit constraint is always binding through most of the considered period, implying that borrowers have been credit constrained through most of the period. This is not an imposed result of the model since both credit constraints would become nonbinding if the patience of the borrowers were estimated to a sufficiently high value. The LTV constraint was binding in 1979-1984, 1991-1997, and 2007-2015. The DTI constraint was binding in the end-1970s, 1987-1991, 1998-2007, and 2015-2017. Both constraints were nonbinding in 1985-1986. The LTV constraint generally binds during and after recessions, and the DTI constraint generally binds in expansions.

The estimation also identifies historical shocks to the credit limits imposed by the credit constraints. Through the whole sample, a punctual time-wise correspondence exists between historical events and credit shock innovations. Positive shocks are evident around the financial deregulation in the start/mid-1980s, the easement of risk management practices of banks in 1998-2005, and the introduction of the Home Affordable Refinance Program and the Home Affordable Modification Program and reduction in mortgage rates in 2009-2010. Negative shocks are evident around the Stock Market Crash of 1987, the Savings and Loan Crisis of 1986-1995, and the eruption of the Subprime Crisis of 2007-

[3]I also construct and estimate a model that only has an occasionally binding LTV constraint and is otherwise identical to the baseline model. The marginal data density favors the baseline model over the LTV model.

2008. The credit shock series closely matches the credit spread shocks that Prieto et al. (2016) find using a different approach, suggesting that the current estimates are valid.

Since the DTI constraint was binding in 1998-2007, the buildup in mortgage debt prior to the recession was caused by looser DTI limits and not necessarily looser LTV limits. This is consistent with the result in Justiniano et al. (2017) that looser LTV limits cannot explain the surge in mortgage debt. Justiniano et al. (2017) also argue that it was an increase in the credit supply that caused the surge in mortgage debt. The results in the present paper do not *per se* reject this hypothesis. Rather, the present results suggest that – if an increase in credit supply occurred – then it translated into a relaxation of DTI limits.

The responses of the model to housing preference and credit shocks match the aforementioned VAR responses to house price and credit shocks. The state-dependent responses in the baseline model are caused by differences across the business cycle in the constraint that binds. Housing preference shocks are amplified by the LTV constraint in contractions since this constraint primarily binds here. Credit shocks move borrowers' housing demand in the same direction as the shock, but this reaction is also only amplified by the LTV constraint when it binds in contractions. The asymmetric responses to credit shocks in the baseline model are caused by differences in the constraint that binds following these shocks. With a positive shock, borrowers reduce their labor supply, which binds the DTI constraint and dampens the effects of the shock through the lower labor supply. By contrast, with a negative shock, borrowers reduce their housing stock, which binds the LTV constraint and amplifies the effects of the shock through the lower housing stock.

I use the estimated model to investigate the optimal timing and implementation of macroprudential policy. I consider how systematic changes in the LTV and DTI limits would have affected the historical evolution in mortgage debt if they had been implemented. Countercyclical DTI limits are very effective at curbing increases in mortgage debt since these increases typically occur in expansions when the DTI constraint is binding. The flip-side of this result is that countercyclical LTV limits cannot prevent mortgage debt from rising since this constraint is typically nonbinding when it occurs. Countercyclical LTV limits can, however, abate the adverse consequences of house price slumps on credit availability by raising credit limits. The result that the primary macroprudential tool should change over the business cycle is not well-documented in economics. Instead, the existing literature focuses on stabilization solely through countercyclical LTV limits.[4]

[4]See, e.g., the Committee on the Global Financial System (2010), the IMF (2011), Lambertini et al. (2013), and Jensen, Ravn, and Santoro (2018).

The rest of the paper is structured as follows. Section 2 discusses how the paper relates to the existing literature. Section 3 presents the threshold VAR model. Section 4 presents the theoretical model. Section 5 presents the Bayesian estimation of the model. Section 6 highlights the non-linear dynamics that the two credit constraints introduce. Section 7 decomposes the historical evolution in credit constraints and limits. Section 8 conducts the macroprudential policy simulation. Section 9 presents county-level empirical evidence on state-dependent mortgage debt elasticities. Section 10 contains concluding remarks.

2 Related Literature

The paper is, to my knowledge, the first to include both an occasionally binding LTV constraint and an occasionally binding DTI constraint in the same model. A small, but growing, theoretical literature already studies house price propagation through occasionally binding LTV constraints. Guerrieri and Iacoviello (2017) demonstrate that the macroeconomic sensitivity to house price changes is smaller during booms (when LTV constraints may unbind) than during busts (when LTV constraints bind). Jensen, Ravn, and Santoro (2018) study how relaxations of LTV limits lead to an increased macroeconomic volatility, up until a point where the limits become sufficiently lax and credit constraints thus generally unbind, after which this pattern reverts. Jensen, Petrella, Ravn, and Santoro (2017) document that the U.S. business cycle has increasingly become negatively skewed, and explain this through secularly increasing LTV limits that dampen the effects of expansionary shocks and amplify the effects of contractionary shocks.

The paper is furthermore, again to my knowledge, the first to document state-dependent effects of house price shocks, using VAR models. Several papers already study the non-linear VAR responses to credit spread shocks. Barnichon et al. (2017) show that shocks to the excess bond premium have asymmetric and state-dependent effects on industrial production and consumption, using a non-linear vector moving average model on U.S., U.K., and Euro area data. First, positive bond premium shocks have large and persistent negative effects on real activity, while negative bond premium have no significant effect on real activity. Second, bond premium shocks have larger and more persistent effects on real activity in contractions than in expansions. Prieto et al. (2016) likewise show that house price and credit spread shocks have significantly stronger effects on GDP growth in crisis periods than in non-crisis periods, using a time-varying parameter VAR model on U.S. data. Davig and Hakkio (2010) and Hubrich and Tetlow (2015) also find that financial stress has larger effects on real activity in crisis periods than in non-crisis periods, using Markov switching VAR models on U.S. data. My paper separates itself from this literature on credit shocks by capturing these shocks as mortgage credit shocks rather than as credit spread shocks.

The existing models with occasionally binding LTV constraints cannot capture the non-linear effects of credit shocks. Since these models rely on a single credit constraint only, their reactions to house price and credit shock are symmetric up until the point where the LTV constraint unbinds. For realistic calibrations of the models, however, this unbinding does typically not occur for small- and medium-sized shocks. For instance, Guerrieri and Iacoviello (2017) need to apply a 20 pct. house price increase in order for their LTV constraint to unbind. Similarly, in Jensen, Ravn, and Santoro (2018), the LTV constraint unbinds lastingly following a large (three standard deviation) positive credit limit shock, but not following other same-sized shocks or with LTV limits below 90 pct. This contrasts the evidence in Barnichon et al. (2017) and Prieto et al. (2016) who observe substantial non-linear effects following single-period unit standard deviation shocks.

Greenwald (2018) already studies the implications of LTV and DTI constraints in a linear, calibrated model, which includes an always-binding credit constraint that is an endogenously weighted-average of a LTV and a DTI constraint. He finds that the DTI constraint – in a symmetric and state-invariant way – amplifies the monetary transmission mechanism. He also finds that DTI credit limits were relaxed during the pre-Great Recession boom. The present paper provides new insights into the implications of such multiple constraints. First, the discrete (nonlinear) switching between the constraints generates asymmetric and state-dependent impulse responses, which are incompatible with linearized models. Second, the occasionally binding constraints imply that homeowners may become credit unconstrained if both constraints unbind simultaneously, unlike with always-binding constraints. Third, the estimation allows for a full-information identification and decomposition of parameters, shocks, variables, and constraints over the long 1975-2017 time period. This contrasts calibration under which the shocks represent an approximate *ad hoc* fit and the model dynamics may be misidentified, potentially leading to misidentification of when the respective credit constraints dominate.[5]

The paper is lastly, still to my knowledge, the first to examine the interacting effects of house price and income growth on equity extraction, using cross-sectional or panel data. A large literature already studies the effects of house price growth on equity extraction

[5]This latter point is important since the relative dominance of the two credit constraints hinges on the magnitude and persistence of house price shocks relative to the magnitude and persistence of income shocks. These quantities, in turn, depend largely on the reduced-form shocks processes, which typically cannot be calibrated accurately due to their reduced-form nature and cross-model inconsistency.

and consumption.[6] However, this literature generally only considers the effects of isolated variation in house prices, rather than of the effects of combined changes in house prices and other variables. A notable exception to this is Bhutta and Keys (2016) who interact house price and interest rate changes, and find that they decidedly amplify each other, in line with the predictions of my theoretical model.

3 Evidence on State-Dependent Macroeconomic Shocks

This section documents a significant state-dependency in the real response to house price and mortgage credit shocks. Using a Bayesian threshold vector autoregression (TVAR) model, I estimate the relationship between consumption, mortgage credit, and the house price. As a novelty, I allow the (detrended) house price to switch the relationship between the three variables across two regimes.

The threshold VAR(p) model contains $K = 3$ variables, and is given by:

$$Y_t = \begin{cases} \mathcal{C}_1 + \mathcal{B}_{1,1}Y_{t-1} + \ldots + \mathcal{B}_{1,p}Y_{t-p} + u_{1,t} & \text{if } q_{t-1} \leq r \\ \mathcal{C}_2 + \mathcal{B}_{2,1}Y_{t-1} + \ldots + \mathcal{B}_{2,p}Y_{t-p} + u_{2,t} & \text{if } q_{t-1} > r, \end{cases} \tag{1}$$

where $\mathbb{E}\{u_t\} = 0$, $\mathbb{E}\{u_{1,t}u'_{1,t}\} = \mathcal{S}_{1,t}$, and $\mathbb{E}\{u_{2,t}u'_{2,t}\} = \mathcal{S}_{2,t}$. The objects in (1) denote for regimes $i \in \{1,2\}$: Y_t is a $K \times 1$ variable vector, $\mathcal{C}_i$ is a $K \times 1$ intercept vector, $\mathcal{B}_{i,j}\ \forall\ j \in \{1,\ldots,p\}$ is a $K \times K$ coefficient matrix, $u_{i,t}$ is a $K \times 1$ reduced-form error term vector, q_t is the house price, and $r \in \mathbb{R}$ is the house price switching threshold. The VAR order is $p = 2$, following, i.a., Prieto et al. (2016) and Blake and Mumtaz (2017). The value of the house price threshold is estimated along with (1), and has a starting value equal to the mean of the detrended house price.

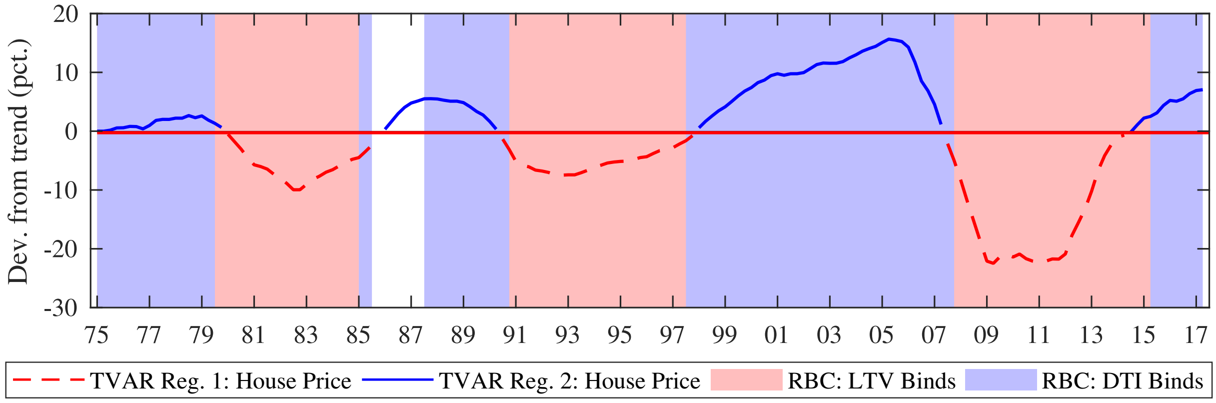
The relationship between the estimated reduced-form error term in (1) and the structural shocks is given by:

$$u_{i,t} = \mathcal{A}_i^{-1}\Sigma_i\varepsilon_t,$$

for regimes $i \in \{1,2\}$ where ε_t denotes a $K \times 1$ vector of structural shocks. Σ_i is a structural $K \times K$ variance-covariance diagonal matrix that measures the size of the structural shocks. $\mathcal{A}_i$ is a $K \times K$ lower triangular matrix that contains ones in the main diagonal and the

[6] Existing papers that study the effects of house price on equity extraction and consumption include Campbell and Cocco (2007), Mian and Sufi (2011), Mian et al. (2013), Bhutta and Keys (2016), Guerrieri and Iacoviello (2017), and Cloyne et al. (2017).

Figure 1: The House Price in TVAR and RBC Regimes



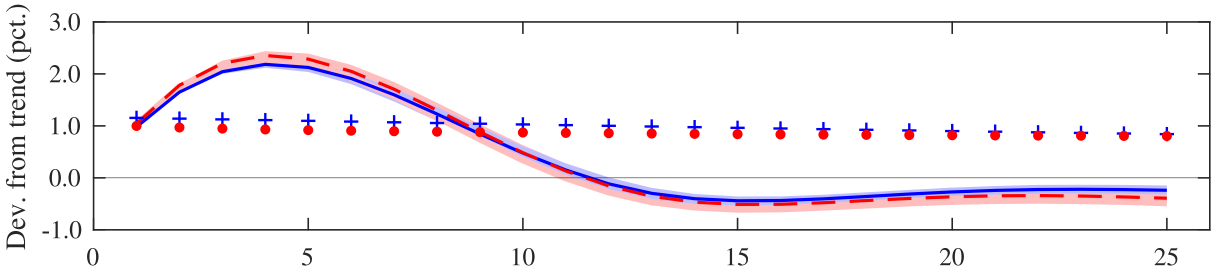
Note: The real house price has been log-transformed, and detrended by a one-sided HP filter with a smoothing parameter of 100,000. The horizontal red solid line indicates the posterior mean of the house price threshold.

contemporaneous relations between the variables in the below diagonal section. $\mathcal{A}_i^{-1}\Sigma_i$ is identified recursively through a Cholesky decomposition of the reduced-form variance-covariance matrix ($\mathcal{S}_{i,t}$). The variables in Y_t are ordered in the following way: consumption, mortgage credit, and the house price. Thus, house price shocks may affect mortgage credit and consumption on impact, and mortgage credit shocks may affect consumption on impact.

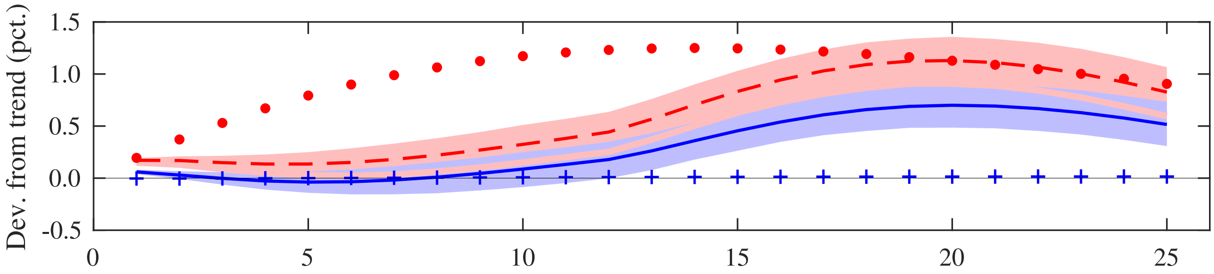
The estimation procedure follows Chen and Lee (1995). This procedure uses a Gibbs sampling Markov chain Monte Carlo algorithm to simulate the posterior distribution of (1). The threshold parameter is sampled inside each loop of the Gibbs algorithm by a Metropolis-Hastings algorithm. The stability of the model is verified within each loop by computing the numeric eigenvalues of the coefficient matrix, and confirming that they are strictly smaller than 1. If the model is not stable, the entire coefficient matrix is redrawn until stability is obtained, as in Blake and Mumtaz (2017).

The estimation sample is identical to the estimation sample that I use for the Bayesian estimation in Section 5. The posterior mean of the threshold parameter is $r = -0.0026$ with a 90 pct. confidence interval spanning $[-0.0010, -0.0036]$. Figure 1 plots the house price with different line styles and colors, depending on whether the TVAR model is in regime 1 or regime 2. Figure 1 also shades the background, depending on whether the LTV or DTI credit constraints bind in the RBC model of Sections 4-5. There is a close regime-wise correspondence between the TVAR and RBC models. When the house price is lower than 0.26 pct. below its trend level, the TVAR model is in regime 1, and the LTV constraint mostly binds in the RBC model. When the house price is higher than 0.26 pct. below its trend level, the TVAR model is in regime 2, and the DTI constraint

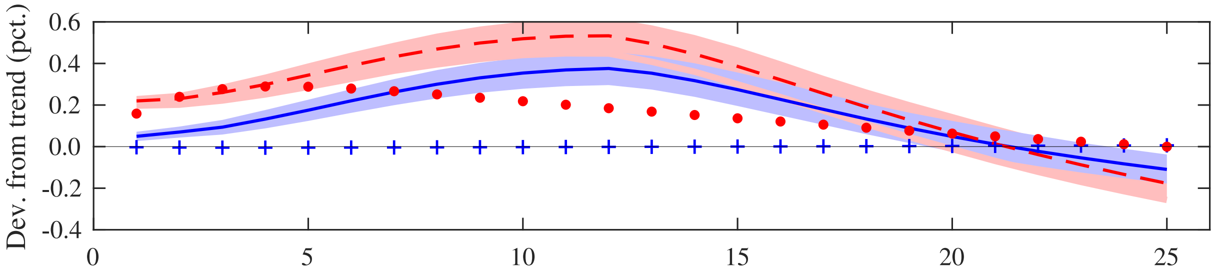
Figure 2: TVAR AND RBC IMPULSE RESPONSES OF A HOUSE PRICE SHOCK



(a) HOUSE PRICE



(b) MORTGAGE CREDIT



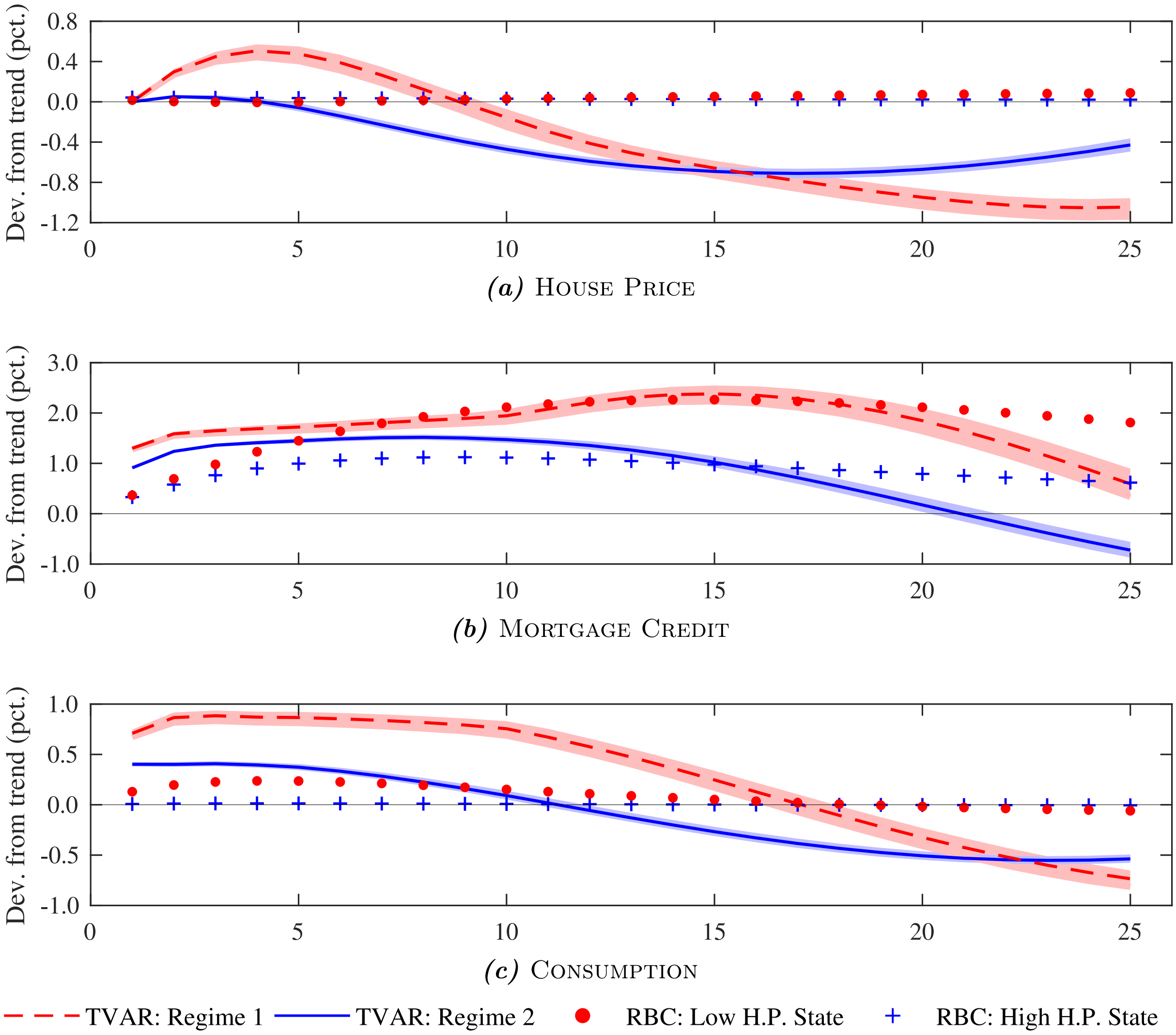
(c) CONSUMPTION

Note: The curves plot the responses of the TVAR model in the low house price regime (red dashed curve) and the high house price regime (blue solid curve) to a positive house price shock. The shaded areas represent the corresponding 90 pct. confidence areas. The markers plot the responses of the RBC model in a low house price regime (red empty marker) and a high house price regime (blue full marker) to a positive housing preference shock. All shocks are single-period unit standard deviation innovations.

mostly binds in the RBC model.

Figure 2 plots the effects of two equally-sized positive house price shocks across the two regimes of the TVAR model. The shocks raise the house price by approx. 2.5 pct. at the peak in either regime. The economy expands in either case, but the peak responses are roughly twice as large in the low house price regime as in the high house price regime. Thus, mortgage credit grows by 1.1 pct. in the low house price regime and by 0.5 pct. in the high regime. Similarly, consumption grows by 0.4 pct. in the low house price regime and by 0.2 pct. in the high regime. Figure 2 also plots the effects of two equally-sized positive housing preference shocks across two house price states of the RBC model. The

Figure 3: TVAR AND RBC IMPULSE RESPONSES OF A MORTGAGE CREDIT SHOCK



Note: The curves plot the responses of the TVAR model in the low house price regime (red dashed curve) and the high house price regime (blue solid curve) to a positive mortgage credit shock. The shaded areas represent the corresponding 90 pct. confidence areas. The markers plot the responses of the RBC model in a low house price regime (red empty marker) and a high house price regime (blue full marker) to a positive common credit shock. All shocks are single-period unit standard deviation innovations.

LTV constraint always binds in the low house price state, and the DTI constraint always binds in the high house price state. The RBC model, at least qualitatively, matches the predictions of the TVAR model. Thus, while the house price responses are nearly identical across the two house price states, the responses of mortgage debt and consumption are larger in the low state than in the high state.

Figure 3 plots the effects of two equally-sized positive mortgage credit shocks across the two regimes of the TVAR model. Like with the house price shock, the economy expands in either case, but the peak responses are highly regime-dependent. Mortgage credit grows by 2.5 pct. in the low house price regime and by 1.5 pct. in the high regime.

Consumption grows by 0.9 pct. in the low house price regime and by 0.4 pct. in the high regime. The house price grows by 0.7 pct. in the low house price regime and by 0.1 pct. in the high regime. This latter observation is particularly interesting since it could indicate that positive credit shocks only increase the usefulness of housing when the house price is low and borrowers are credit constrained by collateral requirements. In addition to these differences in magnitudes, the responses of all three variables are more persistent in the low house price regime than in the high regime. Figure 3 also plots the effects of two equally-sized positive common credit shocks across two house price states of the RBC model, like in Figure 2. The model again, at least qualitatively, matches the predictions of the TVAR model. Thus, the responses of mortgage debt and consumption are larger in the low house price state than in the high state of the RBC model.

4 The Model

The model has a discrete infinite time-horizon with time indexed by t. The economy is populated by two representative households: a patient household and an impatient household. Households consume goods and housing, and supply labor. Goods are produced by a representative firm by combining employment and non-residential capital. The housing stock is fixed, but housing reallocation takes place between the two households. The time preference heterogeneity implies that the patient household lends funds to the impatient household. The patient household also owns and operates the firm and non-residential capital.

4.1 The Patient and Impatient Households

Variables and parameters without (with) a prime refer to the representative patient (impatient) household. The household types differ with respect to their pure time discount factors, $\beta \in (0,1)$ and $\beta' \in (0,1)$, since $\beta > \beta'$. The economic size of each household is measured by its wage share: $\alpha \in (0,1)$ for the patient household and $1-\alpha$ the impatient household.

The patient and impatient households maximize their utility functions:

$$\mathbb{E}_0\left\{\sum_{t=0}^{\infty}\beta^t s_{I,t}\left[\chi\log(c_t-\eta c_{t-1})+\omega_H s_{H,t}\log(h_t)-\frac{\omega_L s_{L,t}}{1+\varphi}l_t^{1+\varphi}\right]\right\} \tag{2}$$

$$\mathbb{E}_0\left\{\sum_{t=0}^{\infty}\beta'^t s_{I,t}\left[\chi'\log(c'_t-\eta c'_{t-1})+\omega_H s_{H,t}\log(h'_t)-\frac{\omega_L s_{L,t}}{1+\varphi}l_t'^{1+\varphi}\right]\right\}, \tag{3}$$

where $\chi \equiv \frac{1-\eta}{1-\beta\eta}$ and $\chi' \equiv \frac{1-\eta}{1-\beta'\eta}$,[7] c_t and c'_t denote goods consumption, h_t and h'_t denote housing, l_t and l'_t denote labor supply, $s_{I,t}$ denotes an intertemporal preference shock, $s_{H,t}$ denotes a housing preference shock, and $s_{L,t}$ denotes a labor preference shock. $\eta \in (0,1)$ measures habit formation in goods consumption. $\omega_H \in \mathbb{R}_+$ and $\omega_L \in \mathbb{R}_+$ weight the (dis)utilities of housing and labor supply relative to the utility of goods consumption.

Utility maximization of the patient household is subject to a budget constraint:

$$\begin{aligned}c_t+q_t(h_t-h_{t-1})+R_{t-1}b_{t-1}+\frac{k_t}{s_{AK,t}}+\frac{\iota}{2\cdot s_{AK,t}}\left[\frac{k_t}{k_{t-1}}-1\right]^2 k_{t-1}\\ =w_t l_t+b_t+\left(R_{K,t}z_t+\frac{1-\delta_K}{s_{AK,t}}\right)k_{t-1}.\end{aligned} \tag{4}$$

Not previously mentioned variables in (4) denote: q_t is the real house price, R_t is the real gross interest rate, b_t is borrowing, k_t is non-residential capital, $s_{AK,t}$ is an investment-specific technology shock, z_t is the utilization rate of non-residential capital, $R_{K,t}$ is the real gross rental rate of non-residential capital, and R_K is the steady-state real gross rental rate of non-residential capital. $\iota \in \mathbb{R}_+$ measures capital adjustment costs.

Utility maximization of the impatient household is subject to a budget constraint:

$$c'_t+q_t(h'_t-h'_{t-1})+R_{t-1}b'_{t-1}=w'_t l'_t+b'_t, \tag{5}$$

where b'_t is borrowing.

Utility maximization of the impatient household is also subject to two occasionally binding credit constraints:

$$b'_t \le (1-\rho)b'_{t-1}+\rho\xi_{LTV}s_{C,t}s_{LTV,t}\mathbb{E}_t\left\{q_{t+1}h'_t\right\} \tag{6}$$

$$b'_t \le (1-\rho)b'_{t-1}+\rho\xi_{DTI}s_{C,t}s_{DTI,t}\mathbb{E}_t\left\{\frac{w'_{t+1}n'_t}{\sigma+R_t-1}\right\}, \tag{7}$$

where $s_{C,t}$ is a common credit shock that shifts the credit limits imposed by both con-

[7] The scaling factors ensure that the marginal utilities of consumption are $\frac{1}{c}$ and $\frac{1}{c'}$ in steady-state.

straints, $s_{LTV,t}$ is a macroprudential LTV limit stabilizer, and $s_{DTI,t}$ is a macroprudential DTI limit stabilizer. $\rho \in [0,1]$ measures inertia in borrowing limits and debt accumulation, following Guerrieri and Iacoviello (2017). $\xi_{LTV} \in [0,1]$ measures the steady-state LTV limit on newly issued debt, $\xi_{DTI} \in [0,1]$ measures the steady-state DTI limit on newly issued debt, and σ measures the amortization rate on outstanding debt. The macroprudential stabilizers ($s_{LTV,t}$ and $s_{DTI,t}$) are only active in Section 8. In Sections 5-7, $s_{LTV,t} = s_{DTI,t} = 1$ applies. The constraints require that homeowners fulfill the following collateral and debt service requirements on newly issued debt in order to qualify for a mortgage loan:

$$\mathbb{E}_t\left\{\frac{b'_t}{q_{t+1}h'_t}\right\} \leq \xi_{LTV} s_{C,t} s_{LTV,t} \qquad \text{and} \qquad \mathbb{E}_t\left\{\frac{\sigma b'_t + (R_t - 1)b'_t}{w'_{t+1}n'_t}\right\} \leq \xi_{DTI} s_{C,t} s_{DTI,t}$$

The LTV constraint can be derived as the solution to a debt enforcement problem, as shown by Kiyotaki and Moore (1997). Appendix A shows that the DTI constraint can be derived separately as an incentive compatibility constraint on the patient household, and that it is a generalization of the natural borrowing limit in Aiyagari (1994). The assumption $\beta > \beta'$ implies that (6) and (7) always hold with equality in (but not necessarily around) the steady-state.

4.2 The Firm

The representative firm produces goods by hiring labor from the patient and impatient households and renting capital from the patient household. The firm operates under perfect competition. The goods are sold as goods consumption, and non-residential investments.

The firm maximizes profits,

$$Y_t - w_t n_t - w'_t n'_t - R_{K,t} z_t k_{t-1}, \tag{8}$$

subject to the available goods production technology,

$$Y_t = (z_t k_{t-1})^{\mu} (s_{Y,t} n_t^{\alpha} n_t'^{1-\alpha})^{1-\mu}, \tag{9}$$

where Y_t denotes goods production, n_t and n'_t denote employment rates, and $s_{Y,t}$ denotes a labor-augmenting technology shock. $\mu \in (0,1)$ measures the goods production elasticity with respect to non-residential capital. (9) is identical to the goods production function in Iacoviello and Neri (2010). They thus also aggregate the labor inputs from the two households through a Cobb-Douglas function. This assumption implies a complementarity across the labor skills of the two households, but simplifies the dynamic and steady-state equilibrium conditions of the model considerably.

4.3 Equilibrium

The model contains a goods market, a housing market, a loan market, and two labor markets. The market clearing conditions are:

$$c_t + c'_t + \frac{k_t - (1-\delta_K)k_{t-1}}{s_{AK,t}} + \frac{f(z_t)}{s_{AK,t}}k_{t-1} + \frac{g(k_t, k_{t-1})}{s_{AK,t}}k_{t-1} = Y_t \tag{10}$$

$$h_t + h'_t = H \tag{11}$$

$$b_t = -b'_t \tag{12}$$

$$n_t = l_t \tag{13}$$

$$n'_t = l'_t \tag{14}$$

4.4 Stochastic Processes

The intertemporal preference, housing preference, common credit, labor-augmenting technology, investment-specific technology, and labor preference shocks follow AR(1) processes. Each shock process has an independent and identically distributed normal stochastic innovation with a constant standard deviation.

5 Solution and Estimation of the Model

5.1 Solution and Estimation Techniques

The model is solved with the solution technique from Guerrieri and Iacoviello (2015). It is necessary to apply a non-linear solution technique such as this one in order to account for the two occasionally binding credit constraints. The model is estimated by Bayesian maximum likelihood with the approach in Guerrieri and Iacoviello (2017) in order to handle the non-linear solution of the model.

The model economy will always be in one of four regimes depending on whether the LTV constraint binds or not and depending on whether the DTI constraint binds or not. When a constraint binds, the households do not expect it to become unbinding. Once a constraint becomes unbinding, however, the households will expect it to become binding again. The households will consequently base their decisions on the expected duration of the current regime. This duration expectation, in turn, depends on the state vector. As a result, the solution to the model will be non-linear in two dimensions. First, it will be non-linear *between* the regimes, depending on which regime that applies. Second, it will be non-linear *within* each regime, depending on the duration expectation of the regime.

A complicating feature of the model is the regime where both constraints bind. In Guerrieri and Iacoviello (2017), the two constraints (a LTV constraint and a zero lower bound) restrict two variables (borrowing and the nominal interest rate). By contrast, in the present model, the two constraints only restrict one variable (borrowing). Consequently, in the regime where both constraints bind, the borrowing limits imposed by the LTV and DTI constraints must be identical. This implies that the right-hand side of (6) must be equal to the right-hand side of (7) in the regime where both constraints bind.

The solution technique from Guerrieri and Iacoviello (2015) performs a first-order approximation of each of the four regimes around the steady-state of a reference regime (one of the four regimes). As a reference regime, I choose the regime where both constraints bind.[8] As a consequence, the calibrated LTV and DTI limits must ensure that – in steady-state, but not necessarily outside steady-state – the right-hand side of (6) is equal to the right-hand side of (7). This restriction on the calibration of the model does, however, not imply that it is not possible to calibrate the model realistically. Instead, as will be evident in Subsection 5.3, a very plausible calibration can be reached.

Borrowing is an observed variable when the model is estimated. It is the common credit shock which ensures that the theoretical borrowing variable matches its empirical measure. When a (or both) credit constraint is binding, the common credit shock has a direct effect on borrowing through the binding constraint. When both constraints are unbinding, the common credit shock has an effect on borrowing through the first order condition of the impatient household with respect to borrowing:

$$u'_{c,t} + \beta'\mathbb{E}_t\big\{(1-\rho)(\lambda_{LTV,t+1} + \lambda_{DTI,t+1})\big\} = \beta'\mathbb{E}_t\big\{u'_{c,t+1}R_t\big\} + \lambda_{LTV,t} + \lambda_{DTI,t}. \tag{15}$$

In order to understand this, consider the following rewriting of the first order condition

[8] I wish to treat the credit constraints symmetrically. I therefore avoid specifying a reference regime where only one constraint binds since this could bias the model towards that regime. The regime where both constraints are nonbinding is furthermore unfeasible as a reference regime since the time preference heterogeneity is inconsistent with households that are not credit constrained in steady-state.

through recursive substitution as:

$$
\begin{aligned}
u'_{c,t} = \beta'^{v}\mathbb{E}_t\Big\{u'_{c,t+v}\prod_{j=0}^{v-1}R_{t+j}\Big\} + \sum_{i=1}^{v-1}\beta'^{i}\mathbb{E}_t\Big\{(\lambda_{LTV,t+i}+\lambda_{DTI,t+i})\prod_{j=0}^{i-1}R_{t+j}\Big\} \\
-\sum_{i=1}^{v-1}\beta'^{i+1}\mathbb{E}_t\Big\{(1-\rho)(\lambda_{LTV,t+i+1}+\lambda_{DTI,t+i+1})\prod_{j=0}^{i-1}R_{t+j}\Big\} \\
+\lambda_{LTV,t}+\lambda_{DTI,t}-\beta'\mathbb{E}_t\big\{(1-\rho)(\lambda_{LTV,t+1}+\lambda_{DTI,t+1})\big\},
\end{aligned}
$$

for $v \in \{\mathrm{v} \in \mathbb{Z} | \mathrm{v} > 1\}$. According to this expression, the current levels of consumption and (via the budget constraint) borrowing are pinned down by the current and expected future Lagrange multipliers for $v \to \infty$. The current multipliers are zero ($\lambda_{LTV,t} = \lambda_{DTI,t} = 0$) when both constraints are unbinding. The expected future multipliers will, however, be positive at some forecast horizon due to the stochastic innovations having a zero mean. The current common credit shock can consequently – through its persistent effects on future credit limits – determine the expected future Lagrange multipliers and consequently consumption and borrowing in the current period.

5.2 Data

The sample frequency is quarterly, and the sample covers the U.S. economy in 1975Q1-2017Q2. The estimation sample contains the following five time-series: 1. Real personal consumption expenditures per capita. 2. Real home mortgage loan liabilities per capita. 3. Real house prices. 4. Real disposable personal income per capita. 5. Aggregate weekly hours per capita.

All series are normalized relative to 1975Q1 and then log-transformed. The series are lastly detrended by a one-sided HP filter (with a smoothing parameter of 100,000) in order to remove the low-frequency components of the series, following Guerrieri and Iacoviello (2017). Data sources and time-series plots are reported in the Online Appendix.

5.3 Calibration and Prior Distribution

Some parameters are difficult for the estimation to identify. These parameters are calibrated using previous studies or steady-state targets. Table 1 reports the calibrated parameters and information on their calibration. The calibrated steady-state DTI limit ($\xi_{DTI} \approx 0.36$) implies that debt services relative to labor incomes *before taxes* may maximally be 28 pct., like in Greenwald (2018). This number is identical to the typical front-end

Table 1: CALIBRATED PARAMETERS

Description		Value	Source or Steady-State Target
Time discount factor, pt. household	β	0.995	Guerrieri and Iacoviello (2017)
Housing utility weight	ω_H	0.20	Steady-state target[a]
Labor supply disutility weight	ω_L	0.10	Normalization[b]
Steady-state loan-to-value limit	ξ_{LTV}	0.774	See text
Steady-state debt-service-to-income limit	ξ_{DTI}	0.364	See text
Amortization rate on outstanding debt	σ	1/104.2	Average original loan term[c]
Depreciation rate, non-residential capital	δ_K	0.025	Standard value
Capital income share of total production	μ	0.33	Standard value
Supply of housing (logarithmic value)	H	1.00	Normalization

[a] The model is calibrated to match the average ratio of owner-occupied residential fixed assets to durable goods consumption expenditures (37.8) over the sample period.
[b] The labor supply disutility weight only affects the scale of the economy, as in Justiniano et al. (2015) and Guerrieri and Iacoviello (2017).
[c] The model is calibrated to match the average loan term (104.2 quarters) on originated loans weighted by the original loan balance during 2000-2016 in Fannie Mae's Single Family Loan Acquisition Data.

(i.e., excluding recurring debt) DTI limit in the U.S. For instance, the U.S. Consumer Financial Protection Bureau writes in its home loan guide: "A mortgage lending rule of thumb is that your total monthly home payment should be at or below 28% of your total monthly income before taxes." (see Consumer Financial Protection Bureau (2015, p. 5)). Since there are no taxes in the model, the labor incomes that the households receive should be treated like after tax incomes. The average labor tax rate was 23.1 pct. in the postwar U.S., according to Jones (2002). The DTI limit accordingly becomes $\frac{0.28}{1-0.231} \approx 0.36$ for incomes *after taxes*.[9]

The calibrated steady-state LTV limit ($\xi_{LTV} \approx 0.77$) ensures that the borrowing limits imposed by the LTV and DTI constraints are identical in the steady-state (cf., the discussion on the solution of the model in Subsection 5.1). The limit is well within the range of typically applied LTV limits (e.g., Liu et al. (2013) and Liu et al. (2016) use 0.75, Justiniano et al. (2017) use 0.80, and Iacoviello and Neri (2010), Lambertini et al. (2013), and Justiniano et al. (2015) use 0.85).

Table 2 reports the prior distributions of the estimated parameters. The prior means of the wage share parameter ($\alpha = 0.66$), the impatient time discount factor ($\beta' = 0.984$), and debt inertia ($\rho = 0.25$) follow the prior means in Guerrieri and Iacoviello (2017). The

[9] A sanity check of this calibration is to compare the implied steady-state annual loan-to-income limit, which is $\frac{b'}{4 \cdot w'n'} \approx 6.2$, to the loan-to-income limit that the Prudential Regulation Authority of the Bank of England has implemented for the U.K. Under this regulation, mortgage lenders may maximally extent 15 pct. of all regulated mortgage loans to households whose loan-to-income ratios are above 4.5 *before income taxes* (see Bank of England (2014a,b)). For mortgage lending outside the most risky 15 pct., the loan-to-income limit accordingly becomes $\frac{4.5}{1-0.231} \approx 5.9$ times their annual income *after taxes*.

Table 2: Prior and Posterior Distributions

	Prior Distribution			Posterior Distribution					
				Baseline			Only LTV Constraint		
	Type	Mean	SD	Mode	5 pct.	95 pct.	Mode	5 pct.	95 pct.
Structural Parameters									
α	B	0.66	0.15	0.6209	0.6137	0.6281	0.7180	0.6925	0.7434
β'	B	0.984	0.006	0.9943	0.9942	0.9944	0.9946	0.9945	0.9946
η	B	0.50	0.15	0.5883	0.5740	0.6026	0.6270	0.6057	0.6482
φ	N	4.00	0.50	5.9359	5.7090	6.1628	7.5320	7.0909	7.9731
ρ	B	0.25	0.15	0.1769	0.1660	0.1878	0.2155	0.2015	0.2295
ι	N	10.0	2.00	2.8883	2.6496	3.1270	1.9100	1.8432	1.9768
Deterministic Structure of Shock Processes									
IP	B	0.50	0.20	0.7311	0.7182	0.7440	0.7131	0.6896	0.7366
HP	B	0.50	0.20	0.9889	0.9876	0.9902	0.9851	0.9826	0.9875
CC	B	0.50	0.20	0.9489	0.9437	0.9541	0.9974	0.9959	0.9989
AY	B	0.50	0.20	0.9320	0.9257	0.9383	0.9260	0.9141	0.9379
LP	B	0.50	0.20	0.9991	0.9987	0.9995	0.9980	0.9969	0.9991
Standard Deviations of Innovations									
IP	IG	0.01	0.10	0.0373	0.0316	0.0430	0.0347	0.0178	0.0517
HP	IG	0.01	0.10	0.0412	0.0353	0.0471	0.0488	0.0436	0.0541
CC	IG	0.01	0.10	0.0180	0.0138	0.0222	0.0217	0.0187	0.0248
AY	IG	0.01	0.10	0.0514	0.0450	0.0578	0.0656	0.0589	0.0723
LP	IG	0.01	0.10	0.0113	0.0077	0.0149	0.0121	0.0097	0.0145
Marginal Data Density at the Posterior Mode									
Log Value (abs.)					3276.74			3221.13	

Distributions: N: Normal. B: Beta. IG: Inverse-Gamma.
Shocks: IP: Intertemporal preference. HP: Housing preference. CC: Common credit. AY: Labor-augmenting technology. LP: Labor preference.
Note: The prior distribution of β' is truncated with an upper bound at 0.9949.

prior mean of the elasticity of the marginal disutility of labor supply ($\varphi = 4.00$) follows the estimate in Galí et al. (2012). The prior means of the remaining estimated parameters follow the prior means of the corresponding parameters in Iacoviello and Neri (2010).

5.4 Posterior Distribution

Table 2 reports two posterior distributions: One from the baseline model with two occasionally binding credit constraints and one from a model with only an occasionally binding LTV constraint. The difference in marginal data densities across the two models implies a posterior odds ratio of exp(55.61) to 1 in favor of the baseline model, suggesting that the data massively favors the model with two constraints.

The estimates of the wage share parameter ($\alpha = 0.62$), the impatient time discount factor ($\beta' = 0.9943$), and debt inertia ($\rho = 0.18$) in the baseline model are similar to the estimates of the corresponding parameters in Guerrieri and Iacoviello (2017): 0.50, 0.9922, and 0.30. This is comforting considering that these parameters are important in determining when the credit constraints bind. In addition to this, the confidence bounds surrounding the three estimates are considerably smaller than in Guerrieri and Iacoviello (2017). One explanation for this is that the mortgage debt time-series, which is intimately related to these parameters, is included in my estimation sample but not in Guerrieri and Iacoviello's (2017) sample. Another explanation is that, while there is only one fewer variable in my estimation sample than in Guerrieri and Iacoviello's (2017) sample, there are five fewer estimated structural parameters, hence making my point estimates more precise.

6 Asymmetric and State-Dependent Dynamics

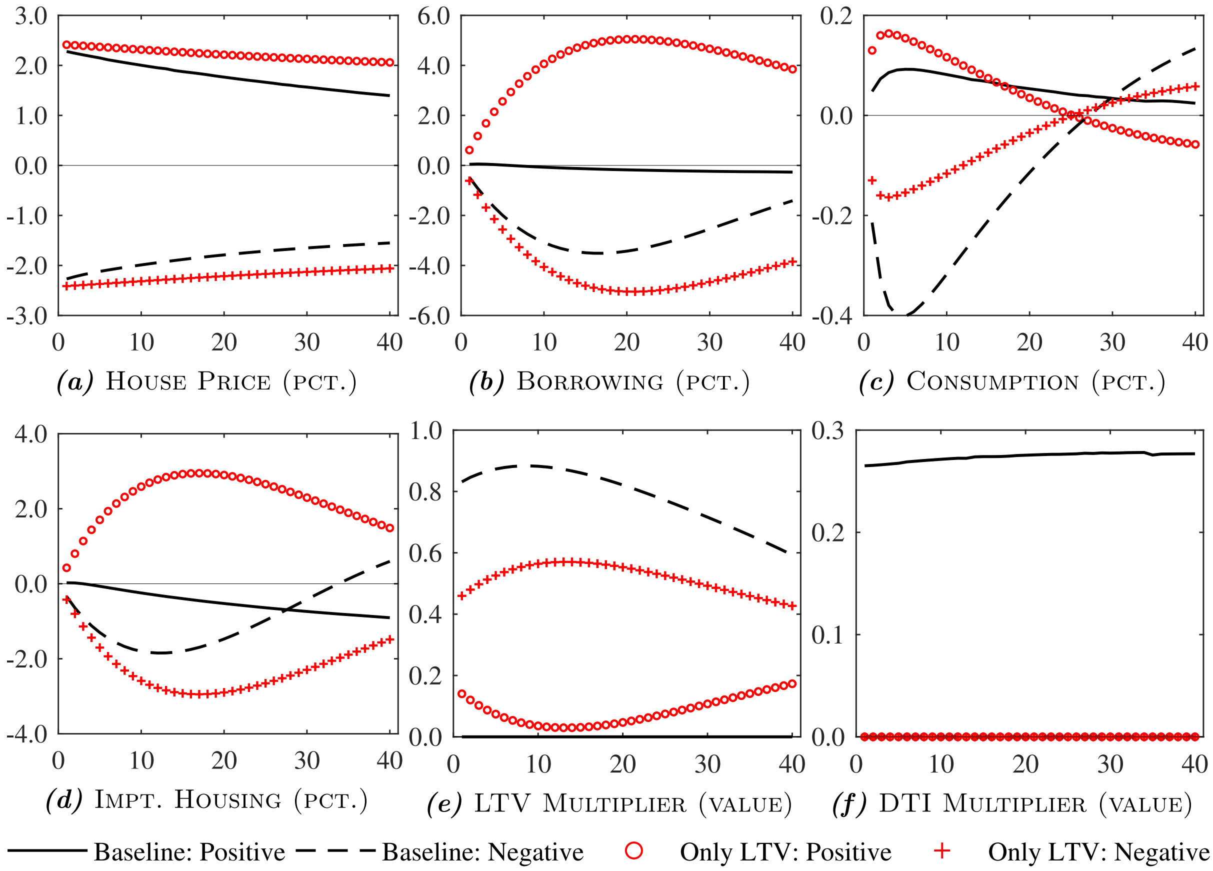
This section illustrates how the two credit constraints cause highly asymmetric and state-dependent responses that are empirically realistic, to housing preference and common credit shocks. The section also illustrates that these responses differ radically from the responses of the LTV model. This model is unable to produce nonlinear responses since its constraint does not unbind following negative shocks and following small- and medium-sized positive shocks, leaving it completely linear following most business cycle shocks.

6.1 Responses to Housing Preference Shocks

Figure 4 plots the effects of four two-standard deviation positive and negative housing preference shocks in the baseline model and in the LTV model. Across the signs of the shocks, the responses of borrowing and consumption are highly asymmetric in the baseline model and completely symmetric in the LTV model.

The asymmetric responses in the baseline model are caused by differences across the signs of the shocks in the constraint that binds. Following the positive shock, the house price increases, but labor incomes are roughly unchanged, implying that the DTI constraint still binds. Borrowing does thus not increase, and its response is consequently indistinguishable from the horizontal axis in Figure 4b. The DTI multiplier increases since it is now the only restricting constraint, and consumption only moves upward by a small amount. Following the negative shock, the house price falls, and the LTV constraint is consequently tighten, causing the impatient household to reduce consumption in order

Figure 4: Asymmetric Impulse Responses of Housing Preference Shocks

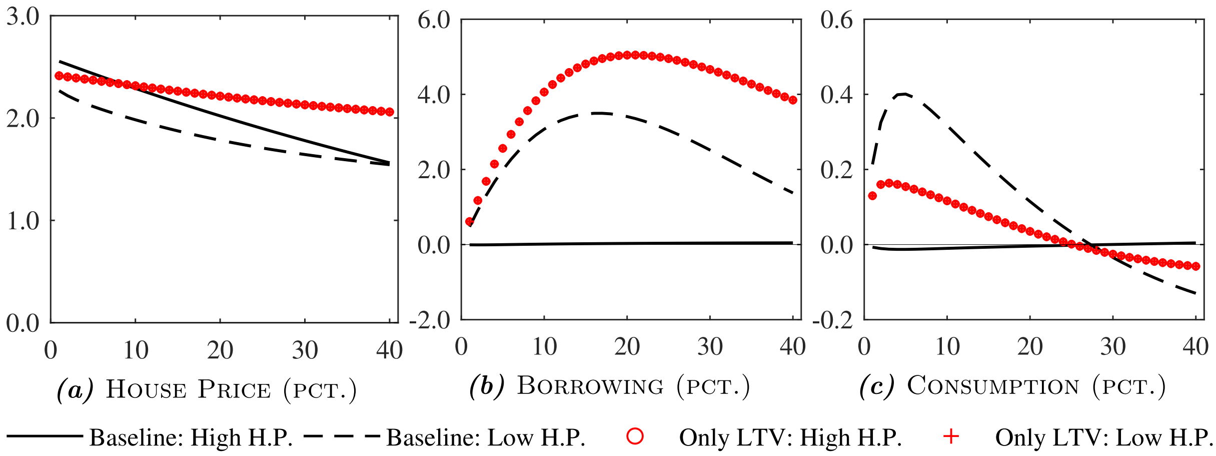


Note: The models are calibrated to the respective posterior modes, reported in Table 2. Vertical axes measure deviations from the steady-state (Figures 4a-4d) or levels (Figures 4e-4f), following positive and negative two-standard deviation shocks.

to delever. The muted response of borrowing in the face of lone house price appreciations is consistent with the county-level panel evidence of Section 9. The difference between the two models suggests that models with only a LTV constraint overestimate the propagation from *lone* housing preference shocks.

Figure 5 plots the effects of four positive two-standard deviation housing preference shocks in the baseline model and in the LTV model in low and high house price states. The responses are highly state-dependent in the baseline model and completely state-invariant in the LTV model. Notably, in the baseline model, the housing preference shock only expands borrowing and consumption in the low house price state, while, in the LTV model, the housing preference shock expands borrowing and consumption in both states. These state-dependent responses are consistent with the responses to house price shocks in the TVAR model of Section 3. The baseline model suggests that the TVAR responses is caused by differences across the business cycle in the constraint that binds. When the house price is low and the LTV constraint binds, this constraint forcefully propagates

Figure 5: State-Dependent Impulse Responses of Housing Preference Shocks



Note: The models are calibrated to the respective posterior modes, reported in Table 2. The impulse responses are computed in the following way. First, the model is simulated with two-standard deviation positive and negative housing preference shocks in period 1. Second, positive and negative two-standard deviation housing preference shocks are added to the expansionary and contractionary impulse matrices also in period 1, and the model is simulated again. Third, differences between the simulations in step one and two are computed. Vertical axes hence measure deviations that are caused by the secondary housing preference shocks.

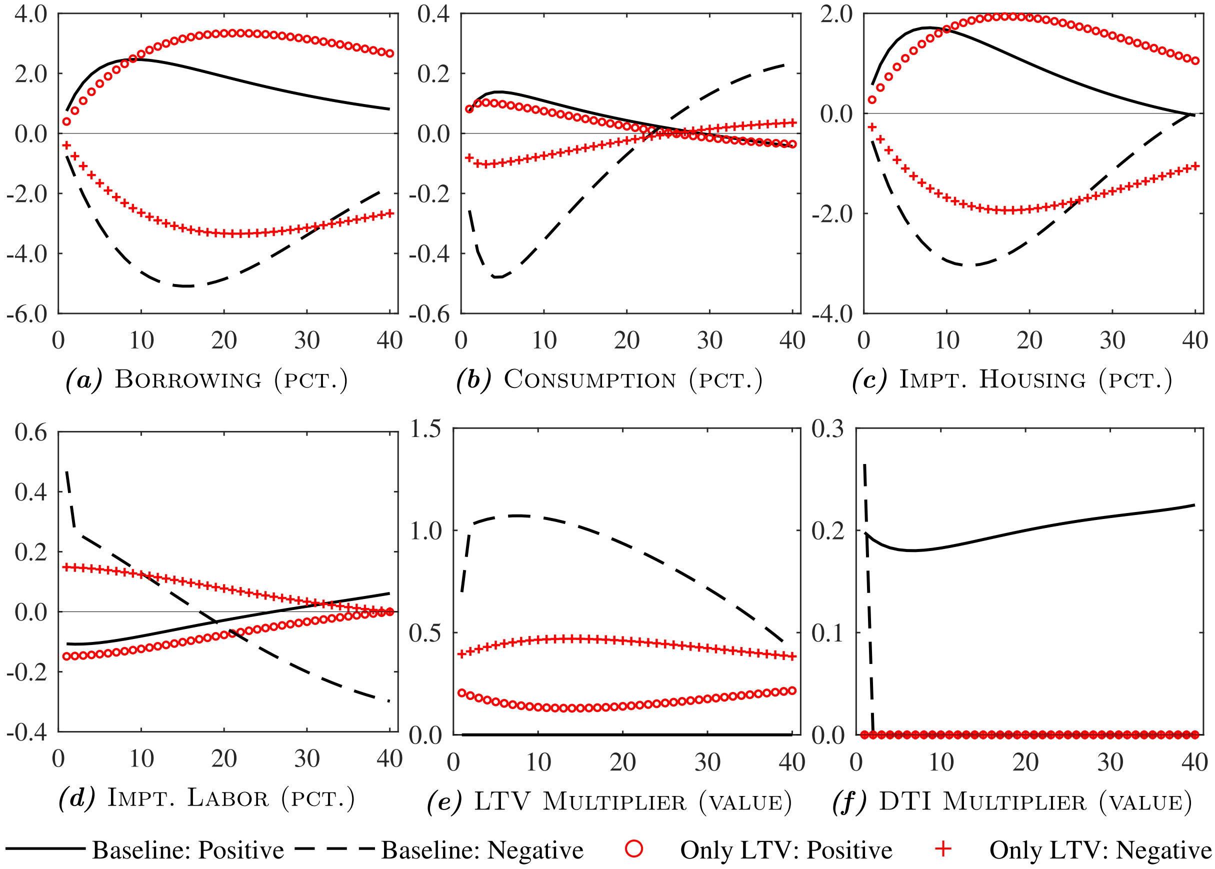
the house price appreciation onto borrowing and consumption. When the house price is already high and the DTI constraint binds, this propagation and amplification channel is switched off, significantly reducing the effects of the housing preference shock.

The symmetric and state-invariant responses in the LTV model arise since its constraint does not unbind, despite the model being shocked with a positive two-standard deviations ("medium-sized") shock. Because the LTV constraint does not unbind, borrowing moves in tandem with the house price, leaving the model completely linear. If the LTV constraint were to unbind, the effects of the house price appreciation would be curbed, leading to a non-linear response. Thus, while the LTV constraint could in principle constitute an important source of business cycle non-linearity alone, the *de facto* linearity of the LTV model suggests that this is not the case for regularly sized shocks.

6.2 Responses to Common Credit Shocks

Figure 6 plots the effects of four two-standard deviation positive and negative common credit shocks in the baseline model and in the LTV model. In both models, a positive shock causes borrowing and consumption to increase, and a negative shock causes borrowing and consumption to fall. However, the responses across the signs of the shocks are highly asymmetric in the baseline model and completely symmetric in the LTV model. In the LTV model, the response of borrowing is twice as large to a negative shock as to a

Figure 6: Asymmetric Impulse Responses of Common Credit Shocks



(a) Borrowing (pct.) ***(b)*** Consumption (pct.) ***(c)*** Impt. Housing (pct.)

(d) Impt. Labor (pct.) ***(e)*** LTV Multiplier (value) ***(f)*** DTI Multiplier (value)

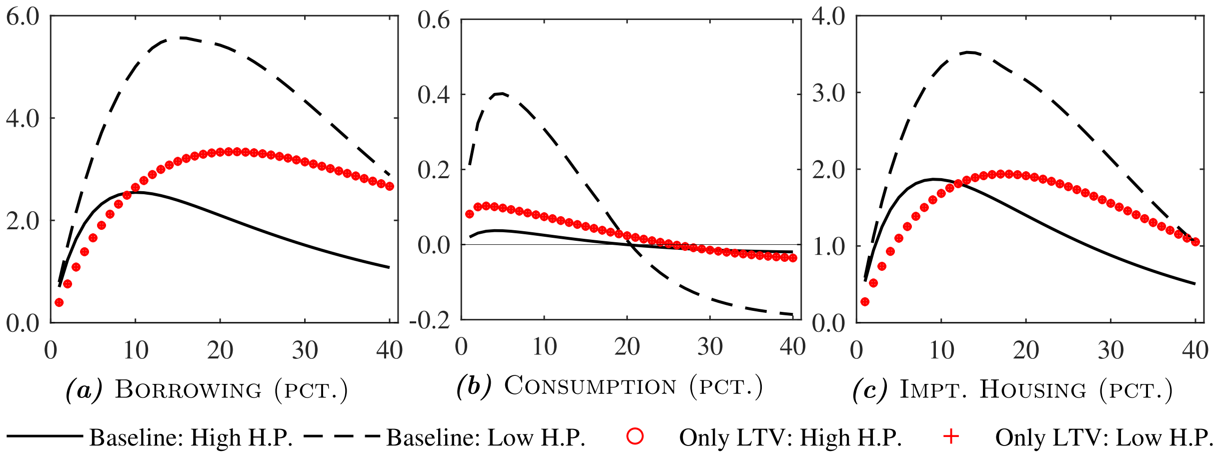
Note: The models are calibrated to the respective posterior modes, reported in Table 2. Vertical axes measure deviations from the steady-state (Figures 6a-6d) or levels (Figures 6e-6f), following positive and negative two-standard deviation shocks.

positive shock, measured at the peak of the impulse response. Likewise, the response of consumption is three times as large to a negative shock as to a positive shock.

The degree of asymmetry in the baseline model is comparable to the asymmetric response to bond premium shocks in Barnichon et al. (2017). They find that a positive unit standard deviation shock reduces consumption significantly for five years (0.4 pct.), while a negative unit standard deviation shock only has a small (0.1 pct.) insignificant expansionary effect. Thus, the effect of a contractionary shock is roughly four times greater than the effect of an expansionary shock, compared to three times greater in the model.

The baseline model suggests that the asymmetric responses in Barnichon et al. (2017) are caused by differences across the signs of the shocks in the responses of labor supply, housing demand, and eventually the constraint that binds. Following the positive shock, the impatient household increases its housing stock and reduces its labor supply because its marginal utility of consumption is lower. This causes the LTV constraint to unbind and the DTI constraint to bind. Importantly, however, because the DTI constraint binds, the

Figure 7: State-Dependent Impulse Responses of Common Credit Shocks



Note: The models are calibrated to the respective posterior modes, reported in Table 2. The impulse responses are computed in the following way. First, the model is simulated with two-standard deviation positive and negative housing preference shocks in period 1. Second, positive and negative two-standard deviation common credit shocks are added to the expansionary and contractionary impulse matrices also in period 1, and the model is simulated again. Third, differences between the simulations in step one and two are computed. Vertical axes hence measure deviations that are caused by the credit shocks.

reduction in labor supply dampens the increase in the debt limit, consequently muting the increase in debt and consumption. Following the negative shock, the impatient household reduces its housing stock and increases its labor supply because its marginal utility of consumption is higher. This causes the DTI constraint to unbind and the LTV constraint to bind. Importantly, now, because the LTV constraint binds, the reduction in the housing stock amplifies drop in the debt limit, consequently amplifying the drop in debt and consumption.

Figure 7 plots the effects of four positive two-standard deviation common credit shocks in the baseline model and in the LTV model in low and high house price states. In both models, the shocks cause an expansion in either state. However, the responses are highly state-dependent in the baseline model and completely state-invariant in the LTV model. In the baseline model, borrowing expands by two-and-a-half times more in the low house price state than in the high state, measured at the peak of the impulse response. Likewise, consumption expands by about six times more in the low state than in the high state. These state-dependent responses are again comparable to the response to bond premium shocks in Barnichon et al. (2017) and to the response to mortgage credit shocks in the TVAR model of Section 3.

The baseline model suggests that the state-dependent responses in Barnichon et al. (2017) and the TVAR model are caused by differences across the business cycle in the constraint that binds. In both states, a positive credit shock increases goods consumption, reduces the marginal utility of consumption, and thus leads the impatient household to demand more housing. However, the implications of this increased housing demand are highly dependent on the constraint that binds. When the house price is low and the LTV constraint binds, the higher housing demand amplifies the leveraging. By contrast, when the house price is high and the DTI constraint binds, the response of housing demand does not have any effects since it is wage income – not the housing stock – that restricts borrowing.

The symmetric and state-invariant responses in the LTV model result from two circumstances. First, the switching between the effective credit constraint – either transversely to the signs of the shock or to the house price states – is by construction missing since there is only one constraint. Second, the LTV constraint fails to unbind, despite the model being shocked with a positive two-standard deviations ("medium-sized") shock. Thus, like in Section 6.1, the *de facto* linearity of the LTV model suggests that its constraint is not alone an important source of business cycle non-linearity for regularly sized shocks.

7 The Historical Development in Credit Constraints

7.1 Loan-to-Value vs. Debt-Service-to-Income Constraints

This subsection gives a historical account of how macroeconomic conditions have determined when the credit constraints were binding. Figure 8a plots the smoothed posterior Lagrange multipliers on the two credit constraints. The LTV constraint binds when $\lambda_{LTV} > 0$, and the DTI constraint binds when $\lambda_{DTI} > 0$. Figure 8b-8c plot the historical shock decomposition of the Lagrange multipliers in deviations from steady-state.[10]

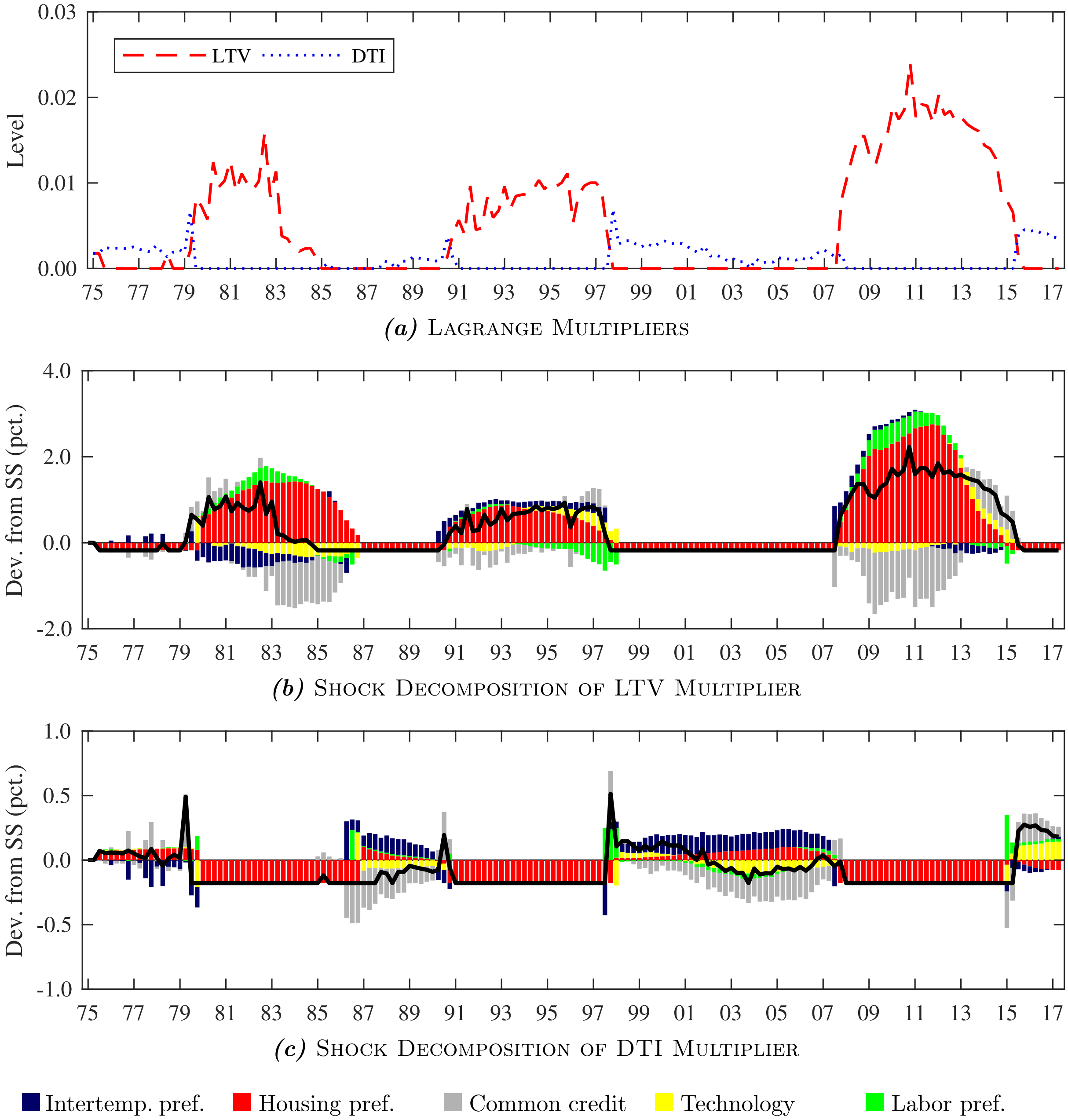
At least one Lagrange multiplier is always positive through most of 1975-2017. Borrowing households have thus been credit constrained through most of the considered period. The LTV constraint generally binds during and after recessions, and the DTI constraint generally binds in expansions. This pattern reflects that house prices are more volatile than personal incomes and that the growth rate of house prices is negatively skewed.[11]

In the end-1970s, the DTI constraint was binding most of the time, reflecting that the oil crises and resulting stagflation had a larger contractionary effect on labor incomes than on the housing market. The LTV constraint became binding during the two recessions of

[10] The steady-state values of the Lagrange multipliers are positive and identical since both constraint are binding in steady-state.

[11] The volatilities of the detrended house price and personal income series are 0.091 and 0.019. The skewness of the growth rate of the detrendend house price series is: -0.86.

Figure 8: Smoothed Posterior Variables



(a) Lagrange Multipliers

(b) Shock Decomposition of LTV Multiplier

(c) Shock Decomposition of DTI Multiplier

Note: The shocks are identified and the decomposition is performed at the mode of the posterior distribution. Each bar indicates the contribution from the respective shock to the considered variable. The shocks were marginalized in the following order: (1) housing preference shock, (2) labor-augmenting technology shock, (3) labor preference shock, (4) intertemporal preference shock, and (5) common credit shock.

the early-1980s. Here, house prices fell due to a deteriorated employment situation (negative labor preference shocks) contracting housing demand and the tight monetary policy of Paul Volcker affecting the housing market disproportionately (negative housing preference shocks). From 1983, three factors contributed to keeping the DTI constraint nonbinding and gradually loosening the LTV constraint. Firstly, the mid-1980s boom improved the employment and housing market conditions (incumbent adverse labor and housing preference shocks disappearing) and caused real wages to grow (positive technology shocks). Secondly, the Great Moderation caused economic optimism (negative intertemporal preference shocks). Thirdly, financial deregulation raised credit limits (positive common credit shocks). As a result, both constraints ended up being nonbinding in 1985Q1-1987Q2. The U.S. thus entered the only period in the sample where the issuance of mortgage loans was not restricted by credit requirements facing borrowers, but by the loan demand of borrowers.

The DTI constraint started to bind again from 1987 because of tighter credit limits and an increased uncertainty about the future (positive intertemporal preference shocks).[12] The LTV constraint became binding again in the early-1990s recession as house prices started to fall, and remained binding until 1998 when house prices started growing rapidly. In the following mid-2000s economic boom, the DTI constraint would remain binding, albeit gradually relaxing due to real wage growth (positive technology shocks) and higher credit limits (positive common credit shocks). This lasted until the onset of the Great Recession when the house price bust caused the LTV constraint to bind again. Recently, from around 2015, a combination of growing house prices and meager wage growth (negative technology shocks) have caused the DTI constraint to bind again.

The shock decomposition confirms the result in Guerrieri and Iacoviello (2017) that the LTV constraint became slack during the housing boom of 1998-2007. However, the decomposition also shows that this unbinding did not imply that homeowners were free to borrow, contrary to the finding of Guerrieri and Iacoviello (2017). Instead, they remained credit constrained because of debt service requirements.

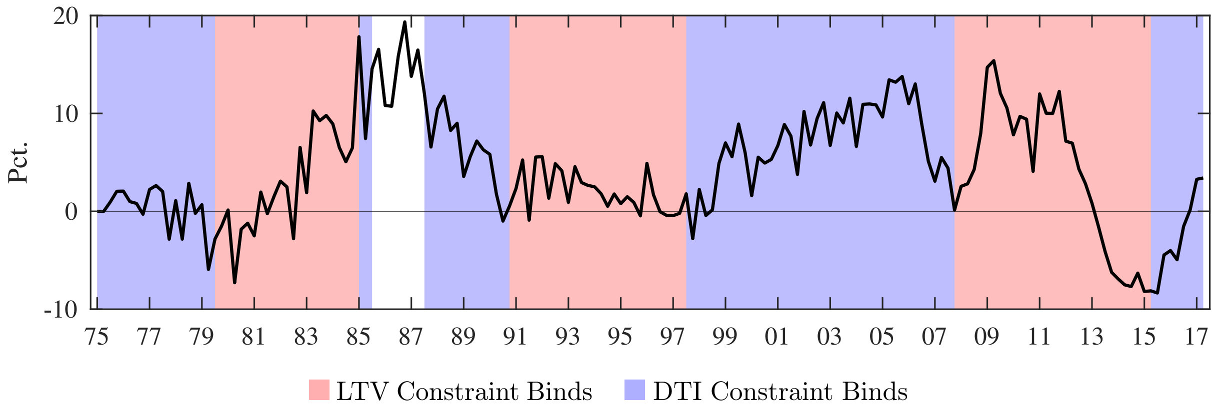
7.2 The Role of Credit Shocks

This subsection focuses on how historical events have shifted the credit limits imposed by the two credit constraints exogenously. Figure 9 plots the estimated values of the common credit shock ($s_{C,t}$), and shade when the respective constraints bind. The shock has shifted the credit limits decidedly several times during the past four decades. The credit constraints are the only wedges between the credit supply of the patient household and the credit demand of the impatient household. The common credit shock consequently captures exogenous shocks to both credit supply and credit demand.

Credit limits were first eased by approx. 20 pct. of their steady-state values in the start/mid-1980s. This relaxation was the likely cause of the first major deregulation of the

[12]The first optimism and then pessimism are reflected in the University of Michigan Consumer Sentiment Index, which grew by 43.4 pct. from 1982 to 1984 and fell by 7.1 pct. from 1984 to 1987.

Figure 9: Smoothed Common Credit Shock



Note: The historical common credit shocks are identified at the posterior mode.

financial sector since the Great Depression. Notably, the Depository Institutions Deregulation and Monetary Control Act of 1980 and the Garn-St. Germain Depository Institutions Act of 1982 deregulated and increased competition between banks and thrift institutions. As a consequence, greater access to alternative borrowing instruments (including adjustable-rate loans) reduced effective down payments and allowed households to delay repayment through cash-out mortgage refinancing, according to Campbell and Hercowitz (2009).

During the Black Monday Stock Market Crash of 1987 and the Savings and Loan Crisis, credit limits were subsequently tightened and eventually returned to steady-state. Importantly, out of 3,234 thrift institutions in 1986, 1,043 institutions were as closed due to losses on mortgage loans before the end of 1995, according to Curry and Shibut (2000). There is a punctual time-wise match between these failures and the negative common credit innovations. Out of $ 519 billion in assets of thrift institutions failing, $ 97 billion failed in 1988, $ 135 billion failed in 1989, $ 130 billion failed in 1990, and $ 79 billion failed in 1991, also according to Curry and Shibut (2000).

Credit limits were again eased in 1998-2005; this time by approx. 15 pct. above their steady-state levels. This observation fits with the widely recognized understanding that the risk management practices of banks were eased in those years due to an excess supply of mortgage loans, which the banks wished to pass on to homeowners. Justiniano et al. (2017) point to various sources of this excess supply. They mention the pooling and tranching of mortgage bonds into mortgage-backed securities, which created assets that were rated safe out of pools of risky mortgage bonds.[13] They also mention the global savings influx

[13] Justiniano et al. (2017) argue that the securitization (i) channeled savings aimed at fixed-income securities with high ratings into mortgage loans, (ii) freed up intermediary capital which had previously been kept due to leverage requirements, and (iii) allowed banks to combine liquid deposits and illiquid

into the U.S. mortgage market following the late-1990s Asian financial crisis. The DTI constraint was binding in 1998-2007. The buildup in mortgage debt prior to the recession was thus caused by looser DTI limits rather than looser LTV limits. This is consistent with the result in Justiniano et al. (2017) that looser LTV limits cannot explain the surge in mortgage debt. Justiniano et al. (2017) also argue that it was an increase in the credit supply that caused the surge in mortgage debt. The results in the present paper do not *per se* reject this hypothesis. Rather, the present results suggest that – if an increase in credit supply occurred – then it translated into a relaxation of DTI limits.

Credit limits were tightened already in mid-2006, reflecting the slowdown of credit markets prior to the eruption of the Subprime Crisis of 2007-2008 (e.g., with the bankruptcy of *Merit Financial, Inc.* in May 2006). The tightening, however, turned out to be short-lived; credit limits were thus rising again already in 2009. This increase coincides with the introduction of the Home Affordable Refinance Program and the Home Affordable Modification Program in March 2009. These programs lowered the debt service payments for existing homeowners who had high LTV ratios or were in delinquency via exemption from mortgage insurance, interest rate and principal reductions, forbearance, and term extension.[14] The increase also coincides with the sharp reduction in mortgage rates in 2008Q4-2009Q2, which the LTV constraint would likely capture as credit shocks. Gelain et al. (2017) also find that credit standards were loosened in 2009, using a LTV constraint without credit inertia.

The validity of the credit shock estimates in Figure 9 is corroborated by Prieto et al. (2016), using a different approach. They find that credit spread shocks contributed negatively to GDP growth in 2007-2008 and positively in 2009-2012, and attribute these latter contributions to the unconventional monetary policy programs launched then. Prieto et al. (2016) also find traces of the start/mid-1980s' deregulation, the Savings and Loan Crisis, and the start-2000s' lax risk management.

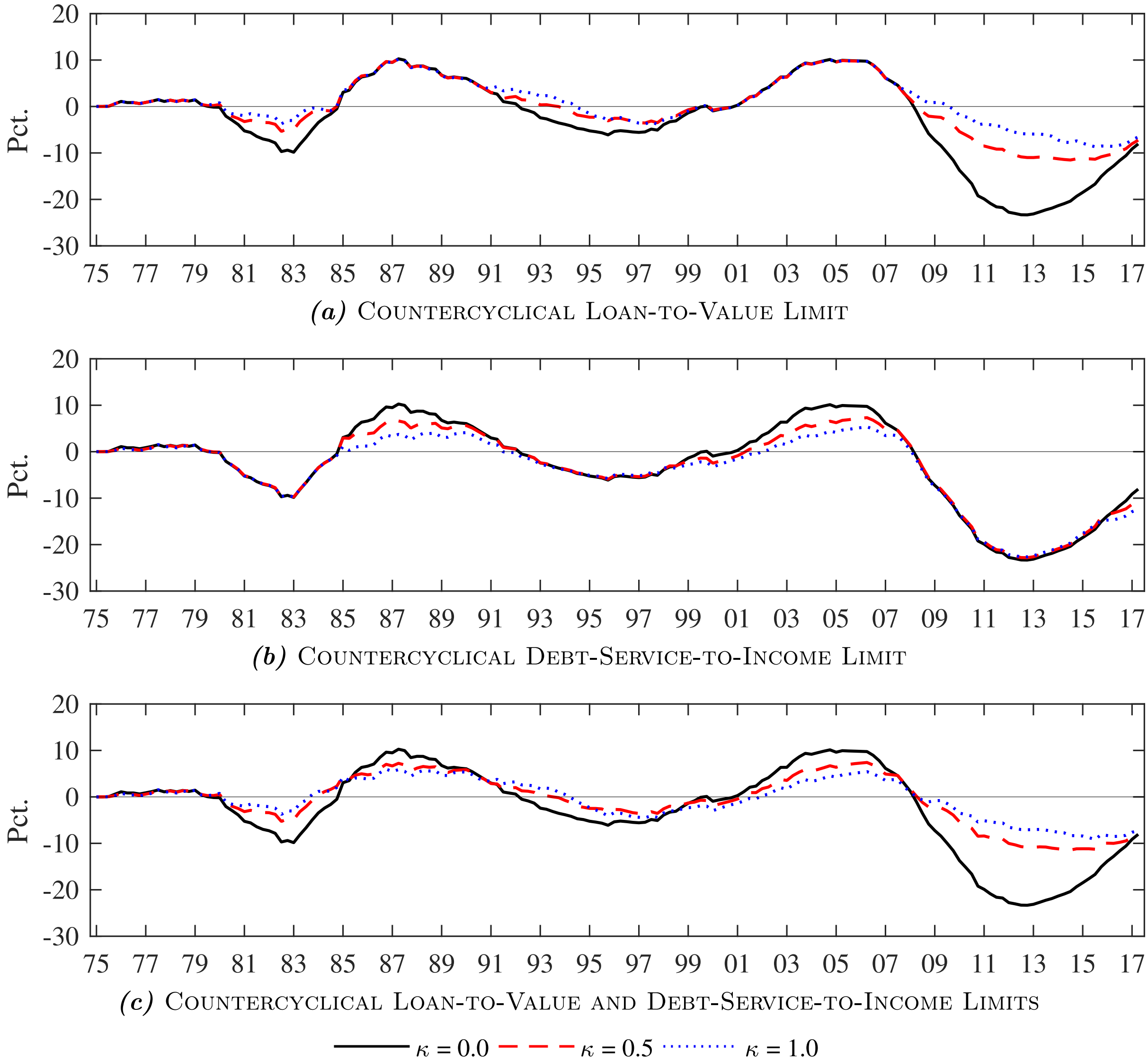
8 Macroprudential Policy Implications

This section examines the implications of countercyclical LTV and DTI limits in the face of occasionally binding LTV and DTI constraints. Figure 10 plots the reaction of borrowing

loans into liquid funds.

[14]Recent studies find sizable impacts of these programs. Agarwal et al. (2017) find that the Home Affordable Modification Program resulted in a 25 pct. reduction in loan payments on average for the one-third of eligible homeowners who participated. Agarwal et al. (2015) find that the Home Affordable Refinance Program resulted in a 20 pct. reduction in loan payments on average for more than 3 million homeowners.

Figure 10: Borrowing under Alternative Macroprudential Regimes



(a) Countercyclical Loan-to-Value Limit

(b) Countercyclical Debt-Service-to-Income Limit

(c) Countercyclical Loan-to-Value and Debt-Service-to-Income Limits

Note: The model is calibrated to the posterior mode, and the historical shocks are identified at the posterior mode. Vertical axes measure deviations from the steady-state.

to the estimated sequence of shocks under four different macroprudential regimes. In the first regime, there is no active macroprudential policy so the credit limits are only shifted by the common credit shock, as in the estimated model. Thus, the observed variables in the model by construction match the data. In the three other regimes, the following policies apply: a countercyclical LTV limit, a countercyclical DTI limit, and countercyclical LTV and DTI limits. The corresponding reactions of consumption and house prices are reported in the Online Appendix. Table 3 reports the standard deviations of borrowing, consumption, and house prices under the four macroprudential regimes.

The countercyclical LTV and DTI limits are introduced as systematic responses to the

Table 3: Standard Deviations under Alternative Macroprudential Regimes (pct.)

Regime Type	None	LTV		DTI		Both	
Regime Strength	0.0	0.5	1.0	0.5	1.0	0.5	1.0
Borrowing	9.10	6.04	5.01	8.24	7.68	5.31	4.10
Consumption	2.54	2.43	2.37	2.52	2.52	2.42	2.36
House Price	9.05	9.01	9.01	9.06	9.04	9.02	9.01

Note: The model is calibrated to the posterior mode, and the historical shocks are identified at the posterior mode.

quarterly year-on-year growth rate of borrowing:

$$\log s_{LTV,t} = 0.75 \cdot \log s_{LTV,t-1} - \kappa_{LTV}(\log b'_t - \log b'_{t-4}) \tag{16}$$

$$\log s_{DTI,t} = 0.75 \cdot \log s_{DTI,t-1} - \kappa_{DTI}(\log b'_t - \log b'_{t-4}), \tag{17}$$

where $\kappa_{LTV} \geq 0$ and $\kappa_{DTI} \geq 0$ measure the degree of countercyclical macroprudential policy. (16)-(17) enter into (6)-(7) so that $s_{LTV,t} = s_{DTI,t} = 1$ no-longer holds.

A strong countercyclical LTV policy ($\kappa_{LTV} = 1.0$) is able to reduce the standard deviations of borrowing and consumption by 45 pct. and 7 pct. relative to the historical baseline. It does so by mitigating the adverse effects of house price slumps on credit availability when the LTV constraint is binding. This stabilization potential was particularly pronounced during and after the Great Recession when the house price drop forced homeowners to delever below the steady-state borrowing level. The flip-side of this result is that countercyclical LTV policy cannot curb increases in borrowing during house price booms since the LTV constraint is typically nonbinding here. Macroprudential policymakers would thus not have been able to prevent the buildup in borrowing in 1998-2005 even if they had reduced the LTV limit in accordance with (16).

A strong countercyclical DTI policy ($\kappa_{DTI} = 1.0$) is able to reduce the standard deviations of borrowing and consumption by 16 pct. and 1 pct. relative to the historical baseline. Unlike the LTV policy, this policy is very effective at curbing increases in borrowing during housing market booms since the DTI constraint is typically binding here. Macroprudential policymakers could thus have avoided the buildup in borrowing in 1998-2005 through stricter DTI requirements.

The lowest volatility in borrowing and consumption is reached by combining the LTV and DTI policies. This reduces the standard deviations of borrowing and consumption by 55 pct. and 7 pct. relative to the historical baseline. In this case, the macroprudential policy effectively changes over the business cycle with a DTI policy in expansions and a LTV policy in contractions. The potential benefits of such policy are not well-documented in economics. The existing literature mostly focuses on stabilization solely through countercyclical LTV limits.[15] The ineffectiveness of LTV limits in expansions and DTI limits in contractions emphasize the necessity of models with both constraints in order to determine the optimal timing and implementation of macroprudential policy.

9 County-Level Evidence on Credit Constraints

The credit constraints of the theoretical model together predict that only if both house prices and labor incomes increase, may homeowners take on additional debt. In this section, I test this prediction by estimating the elasticities of mortgage loan origination with respect to house prices and personal incomes on U.S. county-level panel data. As a novelty, for each variable, I distinguish between the unconditional elasticity and the elasticity given that the other variable is growing.

The dataset contains data on the amount of originated mortgage loans, house prices, and personal incomes across U.S. counties at an annual longitudinal frequency during 2007-2016. The originated mortgage loans data is from the Home Mortgage Disclosure Act (HMDA) dataset of the U.S. Consumer Financial Protection Bureau. I consider originated mortgage loans that are secured by a first or subordinate lien in owner-occupied principal dwellings. The house price data is from the All-Transactions House Price Index for counties of the U.S. Federal Housing Finance Agency. The income and population data is from the Personal Income, Population, Per Capita Personal Income (CA1) table in the Regional Economic Accounts of the U.S. Bureau of Economic Analysis. The start date of the sample is limited by the mortgage loan origination data, which is first available at the website of the U.S. Consumer Financial Protection Bureau from 2007.

[15] The Committee on the Global Financial System (2010) and the IMF (2011) recommend to employ LTV limits as countercyclical automatic stabilizers around a fixed cap. Lambertini et al. (2013) demonstrate that a LTV limit which responds countercyclically to credit growth moderates the fluctuations in output, using a model with an always binding constraint. Jensen, Ravn, and Santoro (2018) demonstrate that a LTV limit which responds countercyclically to output growth likewise moderates the fluctuations in output, using a model with an occasionally binding constraint. The two latter papers furthermore show that a countercyclical LTV limit is welfare-improving compared to a constant limit.

The general regression specification is given by:

$$\begin{aligned}\Delta \log d_{i,t} = \gamma_t + \delta_i + \beta_{hp}\Delta \log hp_{i,t-1} + \beta_{inc}\Delta \log inc_{i,t-1} \\ + \beta^I_{inc}\mathcal{I}_{inc,i,t-1} + \tilde{\beta}_{hp}\mathcal{I}_{inc,i,t-1}\Delta \log hp_{i,t-1} \\ + \beta^I_{hp}\mathcal{I}_{hp,i,t-1} + \tilde{\beta}_{inc}\mathcal{I}_{hp,i,t-1}\Delta \log inc_{i,t-1} + v_{i,t},\end{aligned} \tag{18}$$

where $\mathbb{E}\{v_{i,t}\} = 0$, $\Delta \log$ denotes a log-change, $d_{i,t}$ denotes the amount of originated mortgage loans in county i at time t, γ_t denotes time fixed effects, δ_i denotes county fixed effects, $hp_{i,t}$ denotes house prices in county i at time t, and $inc_{i,t}$ denotes disposable personal income in county i at time t. $\mathcal{I}_{hp,i,t}$ and $\mathcal{I}_{inc,i,t}$ denote growth indicators for house prices and personal incomes in county i at time t. They take the value "1" if their input variable ($x_{i,t}$) is growing (i.e., $\Delta \log x_{i,t} > 0$) and the value "0" if their input variable is stagnant or falling (i.e., $\Delta \log x_{i,t} \leq 0$). β_{hp} measures the unconditional elasticity with respect to house prices, β^I_{inc} measures the discrete effect of personal income growth, and $\tilde{\beta}_{hp}$ measures the elasticity with respect to house prices conditional on personal incomes growing. Likewise, β_{inc} measures the unconditional elasticity with respect to personal incomes, β^I_{hp} measures the discrete effect of house price growth, and $\tilde{\beta}_{inc}$ measures the elasticity with respect to personal incomes conditional on house prices growing.[16]

I treat the lagged house price and personal income variables as exogenous conditional on the year and county fixed effects. The variables in (18) are lagged in order to reduce the risk that omitted time-varying variables bias the results. I refrain from using the housing supply elasticity from Saiz (2010) for three reasons, following Bhutta and Keys (2016). First and foremost, I wish to treat house prices and personal incomes symmetrically. Having an instrument for house price movements may alter the correlation between house prices and loan origination, while preserving the correlation between incomes and loan origination. Thus, the effect of house prices on loan origination would be misidentified relative to the effect of personal incomes on loan origination. Second, the housing supply elasticity is unfeasible as a house price instrument in panel analyses since it does not vary over time. Third, the data covers the housing bust period for which the supply elasticity is, in theory, not a good instrument. In slack periods, negative housing demand shocks should cause similar house price declines in both elastic and inelastic areas due to the durability of housing.

Table 4 reports the ordinary least square estimates of (18). In specification 1, I do not allow for state-dependent elasticities. In this case, the elasticity of loan origination is 0.29

[16] The effective sample period covers 2008-2016 due to the log-change transformation in (18).

Table 4: MORTGAGE LOAN ORIGINATION ACROSS U.S. COUNTIES (2008-2016)

	$\Delta \log b_t$				
	(1)	(2)	(3)	(4)	(5)
$\Delta \log hp_{i,t-1}$	0.291***	-0.0784		0.103	
	(0.0788)	(0.170)		(0.107)	
$\Delta \log inc_{i,t-1}$	0.279***	0.267**	0.281***	0.0809	
	(0.0960)	(0.115)	(0.0909)	(0.113)	
$\mathcal{I}_{inc,i,t-1}$		0.00678			
		(0.0112)			
$\mathcal{I}_{inc,i,t-1} \Delta \log hp_{i,t-1}$		0.548***	0.476***		
		(0.191)	(0.0899)		
$\mathcal{I}_{hp,i,t-1}$				0.0569***	0.0609***
				(0.0141)	(0.00990)
$\mathcal{I}_{hp,i,t-1} \Delta \log inc_{i,t-1}$				0.315**	0.407***
				(0.155)	(0.117)
Observations	24056	24056	24056	24056	24141
Adjusted R^2	0.706	0.709	0.709	0.712	0.711

Note: Year and county fixed effects are included in all specifications. The observations are weighted by the county population in a given year. Standard errors are clustered at the county level, and reported in parentheses. ***, **, and * indicate statistical significance at 1 pct., 5 pct., and 10 pct. confidence levels, respectively.

with respect to house prices and 0.28 with respect to personal incomes. In specifications 2-3, I introduce a house price elasticity that is conditional on personal incomes growing. The unconditional house price elasticity shrinks markedly, and becomes statistically insignificant. I arrive at the parsimonious specification 3 after sequentially having restricted the most insignificant term out and re-estimated the model. Here, the house price elasticity is 0.48 conditional on personal income growth. In specifications 4-5, I introduce a personal income elasticity that is conditional on house prices growing. The unconditional income elasticity shrinks markedly, and becomes statistically insignificant. In the parsimonious specification 5, the personal income elasticity is 0.41 conditional on house price growth.

Table 5 verifies the robustness of the results above in two dimensions. First, it is likely that large negative credit shocks are present in the data around the Great Recession. To the extent that these shocks are time-varying county-specific, they will not be captured by the year and county fixed effects in the model, and consequently bias the results. In order to address this concern, I re-estimate (18) on a sample only containing data for 2013-2016.

Table 5: Mortgage Loan Origination across U.S. Counties: Robustness Checks

	$\Delta \log b_t$					
Sample	2013-2016					Full
	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta \log hp_{i,t-1}$	0.255***	-0.0299		0.148		0.218**
	(0.0883)	(0.212)		(0.113)		(0.0932)
$\Delta \log inc_{i,t-1}$	0.252***	0.241	0.204**	-0.285**		0.295***
	(0.0847)	(0.149)	(0.0898)	(0.145)		(0.0988)
$\mathcal{I}_{inc,i,t-1}$		-0.00760				
		(0.0134)				
$\mathcal{I}_{inc,i,t-1}\Delta \log hp_{i,t-1}$		0.324	0.287**			
		(0.291)	(0.139)			
$\mathcal{I}_{hp,i,t-1}$				0.00485		
				(0.0117)		
$\mathcal{I}_{hp,i,t-1}\Delta \log inc_{i,t-1}$				0.758***	0.605***	
				(0.184)	(0.0979)	
$\Delta \log hp_{i,t-1}\Delta \log inc_{i,t-1}$						4.951***
						(1.377)
Observations	10673	10673	10673	10673	10750	24056
Adjusted R^2	0.834	0.834	0.834	0.837	0.835	0.708

Note: Year and county fixed effects are included in all specifications. The observations are weighted by the county population in a given year. Standard errors are clustered at the county level, and reported in parentheses. ***, **, and * indicate statistical significance at 1 pct., 5 pct., and 10 pct. confidence levels, respectively.

I use 2013 as the first year in the post-recession sample because the post-recession trough in the aggregate level of mortgage debt was in this year. The results from Table 4 continue to hold qualitatively with the post-recession sample. Second, if house price and personal income growth amplify each other as indicated by the conditional elasticities of Table 4, then this should also show up in a continuous interaction term ($\Delta \log hp_{i,t-1}\Delta \log inc_{i,t-1}$). I add such term to specification 1 from Table 4, and find that it is positive at a 1 pct. confidence level.

To sum up, the estimates in this section suggest that there is a substantial state-dependency in the elasticities of mortgage debt. House price and income growth do not by themselves cause mortgage loan origination to increase. Only if they occur simultaneously will homeowners take on additional debt. While I caution a too causal interpretation, this suggests that homeowners face both a collateral requirement and a debt service requirement when they apply for mortgage loans, as in the model of Section 4.

10 Concluding Remarks

[TO BE DONE]

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Appendix

A Derivation of the Debt-Service-to-Income Constraint

This appendix shows that the DTI constraint can be derived as an incentive compatibility constraint on the patient household, and that it is a generalization of the natural borrowing limit in Aiyagari (1994). The derivation is separate from the LTV constraint in the sense that the patient household does not internalize LTV constraint when also imposing the DTI constraint.

The impatient household faces the choice of whether or not to default in period $t+1$ on the borrowing issued to it in period t. Suppose that, if the impatient household defaults, the patient household obtains the right to repayment through a perpetual income stream, commencing at period $t+1$. The payments in the income stream are based on the impatient household's labor income ($w'_{t+1}n'_t$), and decrease by the amortization rate (σ) reflecting a gradual repayment of the loan. The net present value of the perpetual income stream is from a period t perspective consequently:

$$P_t = \frac{w'_{t+1}n'_t}{1+r_t} + (1-\sigma)\frac{w'_{t+1}n'_t}{(1+r_t)^2} + (1-\sigma)^2\frac{w'_{t+1}n'_t}{(1+r_t)^3} + \dots,$$

where r_t is the net real interest rate. Since the income stream is a converging infinite geometric series ($\frac{1-\sigma}{1+r_t} < 1$ applies), its net present value can be expressed as:

$$P_t = \frac{w'_{t+1}n'_t}{\sigma + r_t}$$

Suppose next that it is uncertain whether or not the patient household will receive the income stream that it is entitled to in the case of default. With probability ξ_{DTI}, the household will receive the full stream, and with complementary probability $1-\xi_{DTI}$, the household will not receive anything. The DTI constraint now arises as an incentive compatibility constraint in period t on the patient household. Incentive compatibility requires that the value of the loan about to be lend to the impatient household is not greater than the expected income stream in the event of default:

$$b'_t \leq \xi_{DTI}\mathbb{E}_t\left\{\frac{w'_{t+1}n'_t}{\sigma + R_t - 1}\right\} + (1 - \xi_{LTV}) \cdot 0,$$

since $r_t \equiv R_t - 1$. This constraint is a generalization of the natural borrowing limit in Aiyagari (1994). In his seminal paper, he assumed that households may borrow up to the discounted sum of all their future labor incomes, giving him the following constraint: $b'_t \leq \frac{wn_{min}}{r}$. Aiyagari (1994) thus, in the phrasing of the present paper, assumed that stream payments are certain ($\xi_{DTI} = 1$) and not amortized ($\sigma = 0$).