A Danish Fix for U.S. Mortgage Lock-in?*

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Abstract

We study Danish fixed-rate mortgage contracts, which are similar to those in the United States except that borrowers may repurchase their mortgages at market value. Using Danish administrative data, we show that households buy back debt when mortgage prices fall below par and that household mobility is largely insensitive when existing mortgage rates are below prevailing market rates – unlike in the United States, where mobility falls sharply as rates rise. We develop an equilibrium model explaining these patterns and show that introducing a repurchase-at-market option into U.S. mortgages substantially reduces interest-rate-induced lock-in with limited effects on equilibrium mortgage rates.

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1 Introduction

Recent increases in interest rates have exposed a central friction in fixed-rate mortgage markets. In the United States, borrowers holding mortgages with coupons below market interest rates face strong incentives to remain in their homes, even when moving would otherwise be optimal. Because fixed-rate mortgages ("FRMs") must be prepaid at par, households that move or refinance after rates rise forfeit the embedded value of their low-rate debt. This mechanism generates a pronounced "lock-in" effect (Quigley, 1987; Fonseca and Liu, 2024): household mobility and refinancing activity decline sharply in high-rate environments, with important implications for labor mobility, housing allocation, and monetary transmission. Despite its macroeconomic relevance, there is limited empirical evidence on how alternative mortgage contract designs might mitigate rate-induced lock-in while preserving the benefits of fixed-rate borrowing.

We address this question using the Danish fixed-rate mortgage market. Danish FRMs are similar to U.S. contracts — thirty-year, fully amortizing, freely prepayable at par — but differ in one crucial respect: borrowers may also repurchase their outstanding mortgage at market value at any time. This buyback right allows households to realize capital gains when mortgage prices fall, rather than forfeiting them upon moving or refinancing. Using comprehensive Danish administrative data, we study how this contractual feature shapes refinancing and moving decisions over the interest-rate cycle. To interpret the empirical patterns, we develop an equilibrium model of household mortgage choice that incorporates buyback rights, refinancing frictions, and the tax treatment of mortgage interest and capital gains. This framework allows us to isolate the mechanisms through which contract design affects household refinancing and moving behavior and to conduct counterfactual experiments for the U.S. mortgage market.

We document three main findings. First, Danish households actively repurchase their mortgages when market prices fall below par, monetizing the embedded value of their debt and refinancing at higher interest rates. Second, household mobility in Denmark is largely insensitive to the fact that existing mortgage coupons are below prevailing market rates, in stark contrast to the United States, where moving rates decline sharply as rates rise above outstanding coupons. Third, our model shows that these patterns arise from the interaction of buyback rights with refinancing frictions and tax incentives.

Our counterfactual calculations indicate that introducing a Danish-style buyback option into U.S. fixed-rate mortgages would substantially reduce interest-rate-induced lock-in, preserving household mobility with only modest effects on equilibrium mortgage rates. Our results suggest that contract design plays a central role in shaping household responses to interest-rate shocks.

Our empirical analysis uses comprehensive administrative microdata covering the universe of Danish households from early 2010 to early 2024. We define a prepayment as any event in which a household fully retires its outstanding mortgage balance, whether at par or at market value; we sometimes refer to such events as buybacks. Prepayments arise mainly through two distinct channels: (i) moves, in which the household sells its property and relocates, and (ii) refinancings, in which the household remains in the same property but replaces the existing mortgage with a new loan.

The data reveal three core facts. First, consistent with standard refinancing incentives and with U.S. evidence (Berger et al., 2021), refinancing hazards increase sharply when the market yield prevalent at the time of mortgage origination exceeds the current market yield by 50-100 basis points ("bps"). Danish borrowers actively exercise their par prepayment option, refinancing into lower rates with minimal delay. Second, refinancing hazards also rise markedly when yield gaps[1] — defined as the difference between the mortgage market yield prevailing when a household originated its mortgage and the contemporaneous mortgage market yield — fall below -150 bps. This increase reflects widespread discounted buybacks, whereby households repurchase mortgages below par to realize embedded capital gains and refinance into higher rates. Such behavior is largely absent in the United States, where refinancing activity almost entirely disappears once market rates exceed existing coupons. This contrast raises a central question: why do Danish households optimally replace low-coupon, discounted debt with higher-coupon debt issued near par? Third, and most strikingly, Danish moving hazards are nearly flat across negative yield gaps: households move at similar rates regardless of how far market yields exceed those prevalent at the time mortgages were originated. In the United States, Fonseca and Liu (2024) estimate that a 100 bps decrease

[1] As Section 3.3 will make clear, our yield gap measure is a close, but distinct, analog to the coupon gap measure frequently used in the mortgage lock-in literature, and defined as the difference between a mortgage's coupon and the current market interest rate.

in the coupon gap (a close analog to our yield gap measure) reduces annual moving rates by 69-120 bps; in Denmark, the corresponding effect is economically negligible. The buyback right allows Danish households to move without forfeiting embedded capital gains, effectively eliminating the mortgage lock-in channel. All results are robust across both nonparametric and parametric specifications and to alternative sets of controls. Moreover, to facilitate comparisons with the existing mortgage lock-in literature, we replicate our analysis using the conventional household-specific coupon gap instead of our yield-gap measure. The resulting estimates are qualitatively and quantitatively similar, indicating that our conclusions are not driven by the choice of mortgage incentive measure.

These findings carry immediate macroeconomic relevance. In the U.S., the sharp rate increases of 2022-2023 have frozen housing market activity, with mobility and refinancing at multi-decade lows. Our Danish evidence demonstrates that an alternative institutional design — one that allows borrowers to repurchase their debt at market value — can sustain mobility even in a rising-rate environment, effectively delinking household decisions from the vintage of their existing mortgage.

To rationalize these empirical patterns, we develop an equilibrium model of the Danish FRM market. Households hold prepayable mortgages and periodically receive opportunities to refinance or move, subject to fixed costs. When given an opportunity, a household may (i) prepay at par and refinance or move at the prevailing market rate, (ii) repurchase its mortgage at market price and refinance or move, or (iii) remain inactive. The key institutional distinction from the U.S. is the ability to repurchase debt at market value. Mortgage interest is tax-deductible, creating an incentive to refinance into higher-coupon, par-priced mortgages when rates rise: the larger coupon increases future tax deductions. The resulting trade-off — between prepayment costs and enhanced tax shields — resembles the classic trade-off theory of corporate capital structure (Leland, 1994), applied to household debt. The model predicts refinancing hazards that are "U"-shaped in yield gap, decreasing for negative gaps and increasing for positive ones, and moving hazards that are nearly flat across negative gaps, consistent with our empirical findings.

While our theory emphasizes the role of mortgage interest deductibility, the empirical patterns admit an alternative interpretation. Discounted buybacks may also reflect heterogeneity in households' beliefs about the persistence of interest rate shocks. To explore this possibility, we extend the model to allow households to hold subjective expectations that deviate from market-implied beliefs. When households expect interest rates to decline sooner than the market anticipates, they repurchase discounted mortgage debt more aggressively, intending to refinance again at lower rates in the future. Empirically, both channels may be operative, and discounted buybacks in Denmark are likely shaped jointly by tax incentives and households' rate expectations.

We use the model to evaluate the implications of introducing Danish-style buyback rights into U.S. mortgages. Under the current U.S. system, both moving and refinancing rates decline sharply when market rates rise above outstanding coupons. Allowing borrowers to repurchase at market value largely eliminates the moving distortion, preserving household mobility throughout the rate cycle. Refinancing at negative yield gaps remains muted, however, because U.S. tax law offers weaker mortgage interest deductibility and taxes capital gains from debt forgiveness. Strengthening refinancing rates in that case would require modifications to the U.S. tax code.

Despite these institutional differences, the equilibrium mortgage rate in the U.S. with a repurchase-at-market option is on average only 20 bps higher than under the current system. The intuition is simple: under the current U.S. system, the only prepayments when yield gaps are negative come from movers, who must prepay at par — a windfall to investors holding mortgages trading at a discount, thereby lowering mortgage rates when mortgage markets are competitive. Repurchase-at-market rights eliminate this windfall, but because such moves are infrequent, the effect on equilibrium rates is modest. Importantly, the pricing effect is state dependent and operates in a direction that mitigates affordability concerns. The cost of the repurchase-at-market option is highest when mortgage rates are low and lowest when rates are high—precisely when affordability pressures are greatest. As a result, the Danish system would enhance borrower flexibility and mobility while having only limited effects on equilibrium mortgage rates and housing affordability. Moreover, we show that even this modest pricing effect can be eliminated through a simple adjustment to mortgage contract design: introducing a small prepayment premium fully offsets the average increase in equilibrium mortgage rates while preserving the mobility benefits of the repurchase-at-market option.

We also use the model to quantify the private value households attach to repurchase-at-market rights. A willingness-to-pay calculation shows that the status-quo population of borrowers would be willing to pay approximately 65 bps per year in higher mortgage rates to obtain the buyback option, even after accounting for the higher equilibrium mortgage rates associated with the contract. This value reflects the ability to monetize gains embedded in discounted mortgages, increase the expected present value of mortgage interest deductions through refinancing, and undertake positive-net-benefit moves that would otherwise be forgone because of mortgage lock-in. Although our model does not admit a full welfare analysis, this willingness-to-pay calculation provides a natural money-metric measure of the economic value households assign to repurchase-at-market rights.

Introducing a repurchase-at-market option in the U.S. would require institutional adaptation. In the agency market, it would involve either (i) a modification of the prepayment terms embedded in agency MBS so as to allow borrowers to prepay the lesser of par or market value (and a corresponding adjustment to the GSE guarantee terms), or (ii) the ability for borrowers to repurchase, via brokers, the exact MBS in which their mortgage resides and the subsequent cancellation of such mortgage, alongside the principal reduction of the MBS pool. In the jumbo market, it would require accounting and regulatory adjustments that align banks' balance sheet valuations with market prices, removing disincentives to accept discounted repayments. These changes compare favorably to the main alternatives: assumability and portability rely on discretionary lender approval and complex coordination, and have seen negligible take-up in both U.S. government-backed programs and Denmark despite being formally available — revealed preference evidence that these mechanisms face severe practical frictions. Buyback rights, by contrast, are contractually self-executing at observable market prices and operate through existing refinancing infrastructure. We discuss implementation in detail in Section 5.

Related literature. Our paper contributes to work on mortgage lock-in and household mobility (Quigley, 1987, 2002; Ferreira, Gyourko and Tracy, 2010; Fonseca and Liu, 2024; Liebersohn and Rothstein, 2025; Batzer et al., 2024; Aladangady, Krimmel and Scharlemann, 2025; Qian, Gerardi and Zhang, 2026). These studies document that U.S. FRM borrowers face constraints when market rates rise, with implications for geographic mobility, monetary transmission and house price dynamics. We show that such frictions stem from specific prepayment rules — the requirement that prepayments occur at par — rather than from fixed-rate contracts per se. We also contribute to the literature on mortgage contract design (Campbell, Clara and Cocco, 2021; Guren, Krishnamurthy and McQuade, 2021; Fonseca, Liu and Mabille, 2024) by highlighting transactional flexibility as a distinct dimension with first-order implications for household responses to interest rate shocks.

Our theoretical contribution connects household finance to the trade-off theory of corporate capital structure (Miller, 1977; Leland, 1994). Households in our model face an analogous decision to firms choosing leverage: whether to retain low-coupon debt or refinance into higher-coupon debt that increases the tax shield. This parallel provides a foundation for understanding when discounted mortgage repurchases arise as optimal. We also draw on the literature on heterogeneous beliefs (Harrison and Kreps, 1978; Scheinkman and Xiong, 2003): households who view high rates as temporary repurchase discounted debt more aggressively, even absent tax incentives.

The paper most closely related to ours is Svenstrup and Willemann (2006), who study the introduction of a Danish-style buyback option in the U.S. mortgage market. Using a two-factor pricing model with stochastic interest rates and house prices, they conclude that the option would reduce the credit premium charged by the GSEs by about 5 bps while increasing borrower coupon rates by roughly 50 bps per year. Their analysis highlights two key channels through which the buyback option creates value: it reduces credit risk by providing underwater borrowers an alternative to default and mitigates rate-induced lock-in.

Our paper differs in several important respects. First, we bring data to bear on the question. Using Danish administrative microdata, we document how buyback rights are used in practice and how they affect household mobility — providing empirical discipline absent from earlier work. Second, our model features households that optimally choose when to move, refinance, or repurchase their mortgage, rather than relying on reduced-form prepayment and default hazards. This distinction is quantitatively important because the cost of the buyback option depends on how frequently borrowers move when rates are high and how moving rates vary with yield gaps. In contrast to the constant moving intensity assumed in the PSA-style specification of Svenstrup and Willemann (2006), we estimate lower and state-dependent moving rates, which leads them to obtain a larger option cost than we do. Third, while their analysis evaluates the option value at a single point in the interest-rate state space, we compute equilibrium mortgage rates across the ergodic distribution of interest rates and show that the option cost is strongly state dependent — highest when rates are low and negligible when rates are high. Finally, because our framework is an equilibrium model with endogenous household behavior, it allows us to conduct counterfactual policy experiments that lie beyond the scope of a pricing model.

The remainder of the paper proceeds as follows. Section 2 describes the Danish mortgage market. Section 3 presents our empirical analysis. Section 4 develops the equilibrium model and counterfactual calculations. Section 5 discusses U.S. implementation and alternative mechanisms. Section 6 concludes.

2 Institutional details

The Danish mortgage market is one of the most sophisticated and stable capital-market-based housing finance systems in the world. It combines features familiar to U.S. observers — most notably, the widespread use of long-term fixed-rate prepayable mortgages — with several important institutional differences that we describe below. Greater details can be found in Frankel et al. (2004) and Berg, Nielsen and Vickery (2018).

2.1 Balance principle

Danish mortgage lending is conducted almost exclusively by specialized mortgage banks, which finance their loans by issuing covered bonds under a "balance principle." Each mortgage loan is matched by the issuance of a corresponding bond with identical cash flows, ensuring that the mortgage bank bears no interest rate or prepayment risk. Payments from borrowers are passed through directly to bond investors. The mortgage bank retains ownership of the loans and bears credit risk, but these risks are mitigated by conservative regulation — loan-to-value limits (80% for owner-occupied homes), full recourse against borrowers, and efficient foreclosure procedures. The mortgage bank also charges a separate credit fee to bear such risk. This institutional design has historically produced very low credit losses, even during housing downturns.

2.2 Fixed-rate mortgages and par prepayment

In Denmark, approximately half of all mortgages are 30-year fixed-rate, fully amortizing loans with a par prepayment option.[2] In contrast to the U.S., where mortgage rates are quoted on a nearly continuous scale, Danish FRM borrowers choose among a discrete set of coupon rates, typically spaced 50 bps apart. At origination, borrowers generally select the highest coupon for which the corresponding covered bond trades slightly below par, so that mortgage proceeds are received at a small discount relative to the mortgage's face value. Mortgage loans originated by the same mortgage institution with the same coupon and maturity are pooled into common covered-bond series, allowing prepayment risk to be shared across a large number of borrowers and creating deep and liquid secondary markets for Danish mortgage bonds. Borrowers can refinance at any time without penalty, and capital-market investors in Danish covered bonds — much like investors in U.S. agency mortgage-backed securities (thereafter, "MBS") — bear prepayment and interest rate risk but not credit risk. Both systems rely on deep secondary markets that distribute these risks to a broad investor base. This shared funding model helps explain why Denmark and the U.S. belong to a very small set of countries where long-term, freely prepayable FRMs are widely available.

2.3 The distinctive Danish innovation: repurchase at market value

The key institutional difference between the Danish and U.S. systems lies in how mortgages can be extinguished when interest rates rise. In Denmark, a borrower may repurchase the outstanding mortgage by buying the corresponding covered bonds in the secondary market and delivering them to the lender. Because bond prices fall when rates rise, this allows the borrower to retire the debt below par — effectively realizing a capital gain. U.S. borrowers, by contrast, can only prepay at par and are subject to

[2] Figure A-1 reports, year by year in our microdata, the number of fixed-rate and adjustable-rate mortgages. Over our sample period, approximately 48% of all mortgages are fixed-rate. The remaining loans are classified as adjustable-rate mortgages ("ARMs"). In the Danish context, this category includes mortgages with an initial fixed-rate period ranging from 1 to 5 years, after which the interest rate resets at prevailing market rates (so-called "flex" loans). A subset of these ARMs also feature interest-only repayment during the initial period.

"due-on-sale" clauses that require repayment upon property transfer.[3][4] We will show in our paper that this "repurchase-at-market-value" feature has far-reaching implications.

2.4 Taxation

The tax treatment of mortgage interest and of capital gains realized by Danish households upon discount repurchases are the last institutional elements discussed in this section. These features are essential, as they help rationalize why Danish households may find it optimal to repurchase low-coupon, discount mortgages and refinance them with higher-coupon, par-priced mortgages when interest rates rise. In both the U.S. and Denmark, mortgage interest is tax-deductible, subject to specific limitations. In Denmark, mortgage interest is classified as "negative capital income" and, since 2002, has been subject to an effective flat tax rate of 33% (Gruber, Jensen and Kleven, 2021).[5] In the U.S., following the Tax Cuts and Jobs Act of 2017, mortgage interest remains deductible for households that itemize, but only for interest payments on mortgage principal up to USD 750,000 (Ambrose et al., 2022; Scharlemann and Van Straelen, 2024).[6] Finally, while gains realized by Danish households from repurchasing mortgages at a discount are not taxable,[7] the corresponding tax treatment in the U.S. — if such discount repurchases were feasible for fixed-rate mortgage borrowers — is less clear. Such gains could be treated as cancellation-of-indebtedness income and therefore taxed as ordinary income,[8]

[3] As with FHA mortgages in the U.S., the Danish mortgage system permits loan assumption by a homebuyer, potentially reducing lock-in effects (Berg, Nielsen and Vickery, 2018). We show in Section 5.2, however, that assumptions occur at negligible frequency relative to discounted mortgage repurchases.

[4] Another difference is that Danish households can generally refinance irrespective of home equity or credit conditions, whereas U.S. refinancing typically remains subject to underwriting requirements.

[5] In practice, the effective tax rate on negative capital income varies modestly across households because municipal tax rates differ across Danish municipalities. This source of heterogeneity is very small in our data, so we abstract from it and assume a common effective tax rate of 33%.

[6] Households may deduct mortgage interest, charitable contributions, and state and local taxes (up to a statutory cap). When these itemized deductions exceed the "standard deduction," households benefit from itemizing rather than claiming the standard deduction, which amounts to USD 31,500 for married couples filing jointly in 2025.

[7] Danish tax law distinguishes between bond loans (*obligationslån*) and cash loans (*kontantlån*), with only the latter taxing gains from discounted mortgage repurchases. In practice, however, virtually all 30-year fixed-rate mortgages are originated as bond loans, so this distinction has little quantitative relevance for our analysis.

[8] Exceptions include debt discharged in bankruptcy, which is generally excluded from taxable income, and mortgage debt canceled in connection with foreclosure, which may generate either ordinary income

or alternatively as capital gains, analogous to the profits earned by investors who short fixed-income securities and subsequently close these positions at lower prices. In either case, gains generated by discount repurchases would likely be taxable under current U.S. tax law.

3 Empirical analysis

3.1 Data sources and sample selection

The microdata used in this paper come from several Danish government agencies, but is made available to us by Statistics Denmark.[9] We observe the entire Danish population at the beginning of each year, from early 2010 until early 2024.[10] Since we have data on the exact date of various events,[11] for some of our analysis we are able to convert our yearly panel data into a monthly panel data. The unit of observation for our analysis is thus either a household-year or a household-month. While we present most of our main results for household's *primary mortgage* — defined as the largest mortgage per household, measured by its face value at the beginning of that year — our results are robust to including all mortgages for each household in our sample.[12]

In our data, we identify a mortgage prepayment as the disappearance of a loan from a household's balance sheet. We measure refinancing activity when a household prepays an existing mortgage and originates a new mortgage on the same address within the same or the next calendar year. Household moving is identified using changes in

or capital gains depending on whether the debt is recourse or non-recourse.

[9]Mortgage data from 2012 and onward is collected from mortgage institutions by the Danish Central Bank. We are grateful to FinansDanmark for providing us with mortgage data from 2009 to 2011. Income and wealth data is from the Danish tax authorities and demographic data are from the central Danish population register (CPR). Mortgage bond prices are from Værdipapircentralen, but provided to us by the Danish Central Bank, and yield data is from FinansDanmark's public database.

[10]The data is originally recorded at year-end; however, we restructure it so that the end-of-year values serve as the beginning-of-year data for the subsequent year.

[11]Specifically, we have the date at which a household takes on a new mortgage, buys a new property and changes address.

[12]70-80% of mortgage borrowers have only 1 mortgage outstanding at a point in time, while 15-20% of mortgage borrowers have 2 mortgages outstanding at a point in time. See Figure A-2 for the distribution of "number of mortgages" for households with an outstanding mortgage at the beginning of each year, from 2010 to 2024.

registered residential addresses.[13]

The data cover nearly 3 million Danish households per year, corresponding to slightly more than 7 million unique households across the entire sample period. With an average homeownership rate of about 50%, we identify close to 1.5 million homeowners per year and almost 3 million unique homeowners across the full period.[14]

Conditional on being a homeowner, Table 1 reports descriptive statistics for our sample in 2010, in 2023, and for the pooled household-year observations. Over the sample period, 23% of homeowners own their house free and clear of any debt, while 37% have an FRM, and 40% have an ARM. The average maturity of FRMs (resp. ARMs) at origination is 27 years (resp. 29 years), and the average fixed coupon for FRM borrowers is 3% while the average mortgage yield at origination is 3.31%. The average mortgage yield at origination slightly exceeds the average mortgage coupon; it reflects the institutional convention that Danish FRMs are originated with coupons chosen from a discrete set of rates and with the corresponding mortgage bonds issued at a small discount to par (see Section 2.2). Consequently, the par prepayment option is initially slightly out of the money.

In our data over our sample period, the unweighted average refinancing rate for FRM (resp. ARM) borrowers is equal to 14% per year (resp. 6% per year), while these statistics are equal to 18% and 6% respectively when we weight by mortgage face value, suggesting that FRM borrowers who refinance are typically those with larger mortgage face values. Unweighted average moving rate for FRM (resp. ARM) borrowers is equal to 3.3% per year (resp. 4.4% per year), and those statistics are broadly similar when we weight by mortgage face value.

[13] Our analysis focuses on the households' primary mortgage, defined as its largest outstanding loan. As a result we can have that households move without prepaying their primary mortgage. This would be the case if the primary mortgage is linked to a secondary home, while the household moves primary residence. Accordingly, prepayment, refinancing, and moving are related but distinct decisions in the data.

[14] Our estimate of home ownership (50%) is lower than the 60% reported by Eurostat and in the publicly available tables from Statistics Denmark (Statistikbanken.dk). This discrepancy can be attributed to differences in measurement: Eurostat relies primarily on survey data, whereas the Statistics Denmark figures are derived from individuals rather than households. When home ownership is instead calculated as the proportion of dwellings occupied by their owners, using publicly available Statistics Denmark data (BOL104), the resulting estimates are closely aligned with ours.

3.2 Macroeconomic evidence

3.2.1 Prevailing mortgage rates

Panel (a) of Figure 1 plots the evolution of long-term Danish mortgage yields since 2010. This series measures the yield-to-maturity on long-term mortgage bonds funding newly originated fixed-rate mortgages and therefore summarizes the financing cost of new fixed-rate mortgage borrowing.[15] As discussed in Section 2.1, because of the balance principle, these yields closely track households' mortgage borrowing costs. The figure shows a prolonged decline in mortgage rates from 2010 through 2021, followed by a historically unprecedented increase beginning in 2022.

The 2010-2021 decline in mortgage rates reflects the broader fall in European long-term yields associated with subdued inflation, low growth, and accommodative monetary policy. Because Denmark maintains a fixed exchange rate against the euro, Danish interest rates closely followed the euro-area term structure. This low-rate period culminated in 2020-2021, when yields on newly issued long-term FRMs fell below 1%. The tightening cycle that began in 2022 sharply reversed this trend: long-term mortgage yields increased from below 2% in early 2022 to roughly 5.5% by mid-2023.

These two episodes provide substantial variation in households' refinancing incentives. During the period of declining rates, most outstanding mortgages carried coupons above prevailing market rates, making par refinancing attractive. By contrast, the sharp increase in rates after 2022 left many households with mortgages carrying coupons well below prevailing market rates, rendering the par prepayment option far out of the money while creating large liability-related gains that could be monetized via mortgage buybacks. We will exploit this variation to study household prepayment, refinancing, and mobility decisions.

3.2.2 Price of outstanding mortgage bonds

The evolution of Danish mortgage bond prices shown in Panel (b) of Figure 1 mirrors the interest-rate cycle shown in Panel (a). During the prolonged decline in mortgage

[15] The data are publicly available at this link, courtesy of FinansDanmark. The yield-to-maturity takes into account both the coupon and issuance price of the underlying bond, and is computed by FinansDanmark under standard prepayment assumptions.

rates from 2010 through 2021, most outstanding FRM bonds traded close to par because above-market mortgages were repeatedly prepaid (at par) and refinanced. As a result, the distribution of outstanding mortgage prices during that time period remained tightly concentrated around 100.

Beginning in 2022, the sharp increase in mortgage rates caused a broad repricing of outstanding mortgage bonds. As shown in Panel (b) of Figure 1, low-coupon bonds issued during the preceding low-rate period — many carrying coupons between 0.5% and 1.5% — started trading at substantial discounts to par. Because Danish borrowers may repurchase their mortgages at market value, these price declines translate directly into mark-to-market gains on household liabilities. For example, borrowers with 0.5% coupon mortgages maturing in 2050 realized gains approaching 30% of face value between January and October 2022.

Figure 1 therefore illustrates the two refinancing environments that motivate the remainder of the paper. When rates decline, households refinance through the standard par prepayment option. When rates rise, they can instead exploit Denmark's ability to repurchase mortgages below par. Mortgage bond prices therefore influence not only the funding cost of newly originated loans, but also the value of households' outstanding liabilities and the incentives to refinance and move.

3.2.3 Aggregate prepayment, refinancing, and moving rates

Using our microdata, we then compute aggregate mortgage prepayment, refinancing, and moving rates for FRMs and ARMs, and plot the resulting series at the annual frequency in Figure 2 and Figure 3.[16] Several patterns emerge.

First, refinancing rates are consistently higher for FRM borrowers than for ARM borrowers, while ARM borrowers exhibit somewhat higher moving rates. Over the sample period, moving rates average approximately 3.1% per year for FRM borrowers and 4.1% per year for ARM borrowers. Refinancing activity among FRM borrowers is also substantially more cyclical than refinancing activity among ARM borrowers, whereas moving rates for the two groups evolve in broadly similar ways.

[16]We use the terms "buyback" and "prepayment" interchangeably to denote households' exercise of their option to repurchase their mortgage at the lower of (i) par or (ii) market value.

Second, elevated FRM refinancing activity coincides with periods in which long-term rates decline. Refinancing rates rise sharply during 2012–2015 and again in 2019, consistent with households exercising the par prepayment option to refinance into lower borrowing costs. Refinancing activity temporarily slows in 2011, when mortgage rates increase briefly and the par prepayment option moves out of the money.

Third, a distinct refinancing regime emerges in 2022. As interest rates rise sharply and mortgage bond prices fall, FRM refinancing rates increase again — this time not because households refinance into lower rates, but because they repurchase discounted mortgage debt. Households with low-coupon FRMs buy back their outstanding mortgages below par, realize mark-to-market gains on their liabilities, and refinance into higher-rate mortgages issued near par. This behavior is absent among ARM borrowers, whose funding costs adjust mechanically to market conditions and who therefore lack a comparable embedded repurchase option.

Finally, moving rates are comparatively stable. FRM and ARM moving rates trend upward gradually over the 2010s, spike in 2021 during the first year of the COVID-19 pandemic, and then return toward their pre-pandemic levels. Importantly, as mortgage rates rise sharply beginning in 2022, FRM moving rates do not exhibit the pronounced decline observed in the U.S. and commonly attributed to mortgage-rate lock-in. This stability is consistent with the Danish system allowing households to move without forfeiting the embedded value of below-market-rate mortgage debt.

Overall, the aggregate time-series evidence previews the mechanisms studied in the microdata. When rates fall, FRM borrowers refinance through the par prepayment option; when rates rise, they use the repurchase-at-market-value option to realize liability-side gains. Moving rates, by contrast, remain largely insensitive to mortgage-rate fluctuations.

3.3 Microdata evidence

For this analysis, our unit of observation is a household-month, where i denotes the household identifier and t the month. We restrict our focus to households whose primary mortgage is an FRM.

3.3.1 Initial mortgage yield and the yield gap

Let y_t denote the market yield on newly issued long-term mortgage bonds at time t, and let $\tau(i)$ denote the origination date of household i's primary mortgage. The quantity $y_{\tau(i)}$ therefore corresponds to the mortgage market yield prevailing when household i originated its mortgage.

Our microdata contain the coupon of each household's mortgage, but not the discount to par at which the mortgage was originated. This limitation is analogous to that faced by researchers studying U.S. FRMs, who typically observe mortgage coupons but not the points paid or received at origination.[17] Because Danish mortgages are generally originated at a small discount to par, the coupon alone does not fully capture the financing cost incurred by the borrower. We therefore use the contemporaneous market yield $y_{\tau(i)}$ as a proxy for the borrower's origination financing cost. This measure incorporates both the mortgage coupon and the issuance discount and is thus more closely aligned with the economic incentives underlying prepayment and refinancing decisions.

A potential concern is that borrowers originating mortgages at the same point in time may nonetheless face different financing costs depending on the mortgage institution through which the loan is originated. To assess the importance of this issue, the top panel of Figure A-3 plots the price of 2% long-term mortgage bonds issued by the four largest Danish mortgage institutions, while the bottom panel of Figure A-3 reports the cross-sectional standard deviation of bond prices across issuers. The figure shows that bonds with the same 2% coupon and maturity track one another very closely over time. The average cross-sectional standard deviation of prices is approximately 40 bps, corresponding to differences in financing yields of less than 10 bps under standard duration assumptions.[18] Table A-1 shows that similar conclusions hold across coupon categories. Taken together, these results suggest that the market yield on newly issued long-term mortgage bonds provides a good approximation of the financing cost faced by borrowers originating FRMs at a given point in time.

[17] "Points" are upfront fees or rebates paid at mortgage origination. Borrowers can pay points to obtain a lower coupon rate or receive lender credits in exchange for a higher coupon, so the coupon does not uniquely determine the loan's effective financing cost.

[18] This back-of-the-envelope calculation assumes a duration of 5 years at origination.

Motivated by these observations, we define the yield gap for household i at time t as

$$z_{it} := y_{\tau(i)} - y_t, \tag{1}$$

that is, the difference between the mortgage market yield prevailing when the household originated its mortgage and the contemporaneous mortgage market yield.

Panel (c) of Figure 1 plots the average yield gap in our sample over time. Throughout most of the 2010s, the average yield gap fluctuates between 0 and +200 bps as mortgage rates trend downward and FRM borrowers repeatedly refinance into lower-rate mortgages, thereby resetting their yield gap toward zero. By contrast, the sharp increase in mortgage rates during 2022 and 2023 causes the average yield gap to decline abruptly and become substantially negative. In the remainder of the paper, we examine how households' prepayment, refinancing, and moving decisions vary with the yield gap.

3.3.2 Mobility and refinancing responses to the yield gap

We estimate the relationship between mortgage (monthly) prepayment behavior and household i's lagged yield gap using both nonparametric and parametric specifications. Our baseline approach estimates the following nonparametric regression:

$$\mathbb{1}\left(\text{prepay}_{it}\right) = \sum_k \beta_k \mathbb{1}\left(z_{it-1} \in \text{bin}_k\right) + \gamma X_{it} + \epsilon_{it}, \tag{2}$$

where $\mathbb{1}(\cdot)$ denotes the indicator function and lagged yield gaps z_{it-1} are discretized into 50 bps bins. The vector X_{it} contains controls. Specifically, we estimate the model (i) without controls, (ii) with a control set closely mirroring Fonseca and Liu (2024), and (iii) with households' fixed effects.[19]

In addition to the nonparametric specification in equation (2), we estimate a piecewise-linear model that allows the sensitivity of prepayment hazards to differ across positive

[19] When replicating the control vector of Fonseca and Liu (2024), X_{it} includes remaining mortgage maturity, month, and locality-by-year fixed effects, as well as log mortgage balance, log mortgage payment, age, age squared, and household size. Results are robust to additionally including controls for highest achieved level of education, household income, net wealth, and children in the household.

and negative yield gaps:

$$\mathbb{1}\left(\text{prepay}_{it}\right) = \alpha_0 + \beta_0 z_{it-1} + \alpha_1 \mathbb{1}\left(z_{it-1} \geq 0\right) + \beta_1 \mathbb{1}\left(z_{it-1} \geq 0\right) z_{it-1} + \gamma X_{it} + \epsilon_{it}, \quad (3)$$

thereby allowing for distinct slopes on either side of the zero yield-gap threshold, in contrast to the single-slope specification used in Fonseca and Liu (2024). Figure 4 reports the estimated nonparametric relationships between yield gaps and refinancing probabilities (left column) and moving probabilities (right column), as implied by equation (2). Table 2 reports the coefficient estimates from the piecewise-linear specification in equation (3) for moving probabilities.

Several findings emerge from this analysis. First, monthly refinancing hazards increase sharply once the yield gap exceeds approximately 50 bps. This pattern reflects the financial incentive for borrowers to refinance into lower-coupon mortgages, a flexibility that is readily available to Danish households. The increase in refinancing activity occurs only once the yield gap becomes sufficiently positive because Danish mortgages are typically originated at a small discount to par. Consequently, a yield gap of zero corresponds to a mortgage that still trades slightly below par, implying that the par prepayment option remains marginally out of the money. Once the yield gap reaches roughly 50 bps, the prepayment option becomes meaningfully in the money, leading to a pronounced increase in refinancing propensities. A broadly similar pattern has been documented in the U.S., where refinancing activity also rises with the financial gains from refinancing. However, the sensitivity of refinancing hazards appears considerably stronger in Denmark. For example, Berger et al. (2021) estimate that U.S. refinancing hazards increase by approximately 200 bps/month in response to comparable refinancing incentives, compared with nearly 400 bps/month in our Danish sample for our fixed-effect specification. This difference is consistent with Danish borrowers facing fewer refinancing frictions — whether behavioral, informational, or institutional — than their U.S. counterparts (Andersen et al., 2020; Berger et al., 2025).

Second, refinancing hazards rise when the yield gap falls below −150 bps, reflecting the incentive for Danish borrowers to repurchase their mortgages at a discount and realize the mark-to-market gains embedded in their fixed-rate contracts. This behavior stands in sharp contrast to that of U.S. borrowers, whose refinancing rates remain extremely low when yield gaps are negative, indicating a limited response to below-par mortgage pricing (Berger et al., 2021). As we argue in Section 4, the pronounced increase in refinancing hazards for negative yield gaps in Denmark is driven — at least partly — by the tax deductibility of mortgage interest. Although low-coupon discount mortgages and high-coupon par-priced mortgages might have equivalent pre-tax present values, the tax shield on interest payments makes high-coupon, par-priced mortgages more attractive on an after-tax basis.

Third, conditional on a positive yield gap, the moving hazard is modestly upward sloping across specifications. For instance, the estimated slope of 0.046 in Column 2 in Table 2 implies that, when the yield gap is positive, a 100 bps increase in the yield gap raises monthly moving rates by 4.6 bps, or approximately 55 bps per year relative to an unconditional mean of 331 bps per year.[20] A qualitatively similar pattern is documented in Fonseca and Liu (2024), although the estimated gradient in that study is larger than in Denmark. We interpret this relationship as reflecting the increasing value of mortgage prepayment as the yield gap widens: when refinancing at par is attractive, moving — and thereby prepaying the outstanding FRM — becomes more valuable, generating a positive association between yield gaps and mobility for positive gaps.

By contrast, conditional on a negative yield gap, the moving hazard is essentially flat, providing little evidence of a mortgage lock-in effect in Denmark. The precise slope depends on the specification: absent controls, the relationship is mildly downward sloping (slope of approximately -0.012 when expressed using monthly hazard, or -0.138 using yearly hazard), implying that a 100 bps decrease in the yield gap increases annual moving rates by about 14 bps; when using the control set of Fonseca and Liu (2024), the slope becomes mildly positive (slope of approximately 0.016 when expressed using monthly hazard, or $+0.19$ using yearly hazard), implying that a 100 bps decrease in the yield gap decreases annual moving rates by about 19 bps; finally, our fixed-effect specification leads to results somewhere in-between our specification without and with controls. These effects are economically small and stand in sharp contrast to the U.S. evidence, where the estimated slope ranges from 0.69 to 1.20 depending on the specification — i.e. substantially larger than in Denmark. Put differently, Danish households continue to relocate at nearly constant rates even when prevailing market rates substantially exceed

[20]0.046 is the sum of the baseline slope 0.0158 and the positive gap add-on 0.0303.

their existing mortgage coupons, consistent with their ability to move without forfeiting the embedded capital gains in their FRMs.

Finally, panels (a) and (b) of Figure 4 display evidence of "burnout" at high positive yield gaps, with refinancing and moving hazards declining for large yield gaps. This pattern is consistent with a selection effect in which households that are most responsive to incentives act early, leaving behind borrowers who are persistently less responsive to interest-rate incentives. Consistent with this interpretation, the burnout pattern largely disappears once household fixed effects are included (Panels (e) and (f)), indicating that the decline at high yield gaps primarily reflects persistent heterogeneity across households rather than diminishing within-household responsiveness. Importantly, however, incorporating household fixed effects does not materially alter the main conclusions from Table 2: moving hazards remain approximately flat for negative yield gaps and upward sloping for positive yield gaps.

3.3.3 Yield gaps vs. coupon gaps

The recent literature on mortgage lock-in typically measures refinancing incentives using the household-specific coupon gap, defined as the difference between the coupon rate on the borrower's outstanding mortgage and the prevailing market mortgage rate (e.g., Fonseca and Liu, 2024; Liebersohn and Rothstein, 2025; Aladangady, Krimmel and Scharlemann, 2025). Our analysis instead focuses on the yield gap introduced in Section 3.3.1, defined as the difference between the mortgage market yield prevailing when the household originated its mortgage and the contemporaneous mortgage market yield.

This choice has an important econometric advantage. When coupon gaps are used as explanatory variables, cross-sectional variation in coupon gaps may reflect not only differences in mortgage origination dates, but also borrower-specific characteristics that affect the mortgage rate obtained at origination. For example, more financially sophisticated households may obtain lower mortgage rates and may also refinance or move more aggressively. As a result, estimates based on household-specific coupon gaps may be affected by omitted-variable bias. To address this concern, the existing literature typically instruments the household-specific coupon gap with an aggregate coupon gap, defined as the difference between the mortgage market coupon available when the household originated its mortgage and the prevailing mortgage market coupon.

In contrast, all cross-sectional variation in our yield gap measure is driven by the timing of mortgage origination rather than borrower-specific mortgage pricing. Consequently, our baseline specification is closely related to the reduced-form specifications estimated in the existing literature when aggregate coupon gaps are used as instruments for household-specific coupon gaps. Put differently, the identifying variation in our regressions originates from differences in mortgage vintages rather than from cross-sectional differences in borrowers' mortgage rates.

Because all cross-sectional variation in the yield gap stems from origination timing rather than borrower-specific pricing, our baseline yield-gap regressions require no instrument: the yield gap is, by construction, free of the omitted-variable bias that motivates instrumenting household-specific coupon gaps in the existing literature. To facilitate comparison with the existing literature, we replicate all results from Section 3.3.2 using household-specific coupon gaps in place of yield gaps. We define the coupon gap as the difference between the borrower's mortgage coupon and the contemporaneous market coupon, the latter measured as the coupon on newly originated long-term FRMs whose covered bonds trade closest to, but below, par. The nonparametric relationships (equation 2) estimated on coupon gaps appear in Figure A-4 (refinancing) and Figure A-5 (moves), and the piecewise-affine moving estimates (equation 3) in Table A-2, columns (1)-(3). Because the household-specific coupon gap is potentially endogenous, column (4) implements the IV strategy of Fonseca and Liu (2024): we instrument the coupon gap with the aggregate coupon gap — the difference between the market coupon prevailing at the household's origination date and the contemporaneous market coupon — and, in the piecewise specification, instrument the positive-gap indicator and its interaction using the corresponding functions of the aggregate coupon gap. Figure A-6 plots realized coupon gaps against the aggregate instrument and shows a near-45-degree relationship, confirming instrument relevance. Reassuringly, the refinancing and moving relationships estimated on coupon gaps — by OLS or IV — are quantitatively and qualitatively similar to those obtained using yield gaps, and the IV estimates line up closely with the yield gap baseline. This is exactly what the vintage-only interpretation of the yield gap predicts: instrumenting the coupon gap isolates the same origination-timing variation that the yield gap captures directly.

3.4 Takeaways from the empirical analysis

Our empirical analysis highlights important differences between refinancing and moving behavior in the U.S. and Denmark, as well as in how these behaviors respond to yield gaps. These differences have potentially meaningful implications for monetary transmission and housing market dynamics.

The finding that refinancing rates in Denmark are elevated for both positive and negative yield gaps suggests that the transmission mechanism linking monetary policy, mortgage refinancing, and household consumption may differ substantially from that in the U.S. While a systematic and quantitative analysis of these differences lies beyond the scope of the present paper, we investigate them in detail in a companion paper.

Moreover, the relative insensitivity of moving rates to the yield gap (when such gap is negative) in Denmark indicates that household mobility is largely unaffected by the mortgage contract structure, especially amid the recent rise in interest rates. If mortgage-induced lock-in meaningfully impedes geographic mobility — as suggested by evidence from the U.S. — and generates welfare costs through, for example, labor–housing mismatches or inefficient utilization of the housing stock, then policy interventions aimed at mitigating such frictions warrant consideration.

One potential reform would be to incorporate features of the Danish mortgage system that allow borrowers to repurchase their mortgages at market value, thereby preserving mobility when interest rates rise. Section 5 examines the institutional adjustments required to implement such a buyback option in the U.S. context, with particular attention to differences between the agency and jumbo markets. We also discuss alternative mechanisms proposed in the literature — most notably mortgage assumptions and mortgage portability — and assess their effectiveness relative to the Danish framework.

4 Model

In this section, we develop an equilibrium model of the Danish fixed-rate mortgage market to explain households' refinancing and moving decisions. We then use the model to evaluate the introduction of a buyback option into U.S. fixed-rate mortgages and quantify its effects on household behavior and mortgage rates under alternative implementation regimes, with particular attention to mortgage interest deductibility and the taxation of capital gains.

4.1 Setup

We model the economy using a univariate state variable x_t that summarizes the term structure of interest rates. The state follows a diffusion with drift $\mu(x)$, diffusion $\sigma(x)$, and infinitesimal generator $\mathcal{L}$,[21] while the instantaneous short rate is given by the monotone function $r_t = r(x_t)$.

Mortgages are fixed-rate, exponentially amortizing at rate α, and always issued at par.[22] The remaining mortgage balance at time t is therefore $\phi_t = \phi_0 e^{-\alpha t}$. As in Denmark, borrowers may prepay at any time at the lower of par and the market value of the underlying mortgage bond.

Households are risk neutral with subjective discount rate ρ. Let c_t denote the coupon rate on the outstanding mortgage. Refinancing and moving opportunities arrive according to independent Poisson processes with intensities λ and ψ, respectively. These Poisson arrival rates capture behavioral, informational, and institutional frictions that prevent continuous adjustment.

Exercising a refinancing or moving opportunity entails a proportional cost, denoted $\tilde{\kappa}_\lambda$ and $\tilde{\kappa}_\psi$, with cumulative distribution functions F_λ and F_ψ. Refinancing costs capture lender fees and transaction costs, whereas moving costs also incorporate the benefits of relocating and may therefore be positive or negative.

Whenever a household refinances or moves, it replaces its outstanding mortgage with a new par-priced mortgage of identical face value and coupon equal to the prevailing market mortgage rate m_t. If the outstanding mortgage trades below par, the household first repurchases it at market value and realizes the associated capital gain.

Mortgage interest payments are tax deductible at rate θ. As a result, refinancing into a higher-coupon mortgage increases future tax deductions, creating an incentive to refinance when mortgages trade sufficiently below par.

[21] For any twice continuously differentiable function f, $\mathcal{L}f(x) = \mu(x)f'(x) + \frac{1}{2}\sigma^2(x)f''(x)$.

[22] Exponential amortization is a modeling device that avoids introducing an additional state variable. In practice, Danish and U.S. fixed-rate mortgages amortize through standard annuity payments.

Finally, we abstract from household default risk. In Denmark, borrower credit risk is borne by mortgage institutions rather than covered bond investors and is priced separately through institution-specific contribution fees rather than through the mortgage coupon. When a borrower defaults, the mortgage institution repurchases the loan from the covered bond pool at the lower of par and market value, so that from the perspective of covered bond investors, a default is economically equivalent to a prepayment. Moreover, default rates in Denmark are an order of magnitude smaller than prepayment rates,[23] implying that defaults play a quantitatively negligible role in mortgage pricing and household refinancing incentives. We therefore treat mortgages as free of idiosyncratic credit risk and focus exclusively on interest-rate risk and prepayment behavior.

4.2 Household problem

The household chooses when to refinance or move so as to minimize the present value of all future mortgage-related cash flows. Its value function is proportional to the outstanding mortgage balance, $V_t = \phi_t v(x_t, c_t)$, where the normalized value function satisfies

$$v(x,c) := \inf_{a\in\mathcal{A}} \mathbb{E}_{x,c}\left[\int_0^{+\infty} e^{-(\rho+\alpha)t}\left(\left((1-\theta)c_t^{(a)}+\alpha\right)dt + a_t \sum_{\beta=\lambda,\psi}\left(\tilde{\kappa}_{\beta,t} - \max\left(0, 1-p\left(x_{t-}, c_{t-}^{(a)}\right)\right)\right)dN_t^{(\beta)}\right)\right], \quad (4)$$

$$\text{s.t.} \qquad dc_t^{(a)} = \left(m(x_t) - c_{t-}^{(a)}\right)a_t\left(\sum_{\beta=\lambda,\psi} dN_t^{(\beta)}\right). \quad (5)$$

Here, $N_t^{(\lambda)}$ and $N_t^{(\psi)}$ are Poisson processes with intensities λ and ψ, representing refinancing and moving opportunities, and $\mathcal{A}$ denotes the set of admissible binary exercise policies $a = \{a_t\}_{t\geq 0}$ with $a_t \in \{0,1\}$. The function $p(x,c)$ denotes the equilibrium market price of a mortgage with coupon c, while $m(x)$ denotes the equilibrium par mortgage rate. The household observes both the opportunity type and the realized adjustment cost

[23] Figure 10 of Bäckman and Lutz (2025) reports annual repossession rates below 0.20% over 1995–2015, more than an order of magnitude smaller than annual prepayment rates.

$\tilde{\kappa}_{\beta,t}$ before deciding whether to exercise the option.[24]

The normalized value function v satisfies the HJB equation

$$\begin{aligned}(\rho+\alpha)v(x,c) &= \alpha+(1-\theta)c+\mathcal{L}v(x,c)\\ &\quad+\sum_{\beta=\psi,\lambda}\beta\mathbb{E}\left[\min\left[0,v\left(x,m(x)\right)+\tilde{\kappa}_\beta-\max\left(0,1-p\left(x,c\right)\right)-v(x,c)\right]\right]. \end{aligned}\quad (6)$$

The first three terms on the right-hand side capture mortgage principal repayments, after-tax interest payments, and changes in the interest-rate environment. The final term represents the value of refinancing (when $\beta=\lambda$) or moving opportunities (when $\beta=\psi$). Upon receiving such an opportunity, the household either (i) remains inactive, (ii) prepays at par when the mortgage trades above par, or (iii) repurchases the mortgage at market value when it trades below par, thereby realizing the embedded capital gain before refinancing or moving.

4.3 Mortgage pricing

Mortgage markets are competitive. Consider a mortgage with unit face value and coupon c when the term structure state variable is x. Its equilibrium price is

$$p(x,c):=\mathbb{E}_x\left[\int_0^\tau e^{-\int_0^t(r(x_s)+\alpha)ds}(c+\alpha)dt+e^{-\int_0^\tau(r(x_s)+\alpha)ds}\right],$$

with τ the equilibrium prepayment time. Mortgage prices satisfy the pricing equation

$$\begin{aligned}(r(x)+\alpha)p(x,c) &= c+\alpha+\mathcal{L}p(x,c)\\ &\quad+\sum_{\beta=\lambda,\psi}\beta\min\left[0,1-p(x,c)\right]\mathbb{P}\left(v(x,c)>v(x,m(x))+\tilde{\kappa}_\beta-\max\left[0,1-p(x,c)\right]\right), \end{aligned}\quad (7)$$

where $\mathbb{P}(\cdot)$ denotes probability. The first three terms are standard. The final term captures the borrower's prepayment option, which investors are short: par prepayments generate capital losses when mortgages trade above par, whereas repurchases at market

[24] Formally, $\mathcal{A}$ denotes the set of progressively measurable binary processes, so that the exercise decision is taken after observing both the opportunity type and the realized cost draw $\tilde{\kappa}_{\beta,t}$.

value do not generate capital losses when mortgages trade below par.

Finally, the equilibrium mortgage rate is determined by the par-pricing condition

$$p\left(x, m(x)\right) = 1. \tag{8}$$

4.4 Equilibrium

A Markov Perfect Equilibrium ("MPE") is defined as a value function v, optimal refinancing and moving strategy a, a price function p and a mortgage market interest rate $m(x)$ such that:

- given the price function p and mortgage market interest rates m, the refinancing and moving strategy a solves equation (6);
- given the refinancing and moving strategy a followed by households, mortgage prices satisfy the martingale condition (7);
- the mortgage market interest rate satisfies equation (8).

While the existence and uniqueness of an MPE are beyond the scope of our paper, there are certain properties of an MPE that are straightforward to establish. For instance, in any MPE, both the mortgage pricing function p and the value function v will be monotone increasing in c.

These observations allow us to characterize the optimal borrower behavior, conditional on receiving an opportunity to refinance or move. There are two cases to consider. First, assume the realization κ_β of the random prepayment cost $\tilde{\kappa}_\beta$ is strictly positive. In this case, the optimal prepayment strategy of a borrower can be characterized by an inaction region, defined via $\mathcal{I}_\beta(x;\kappa_\beta) := \left[\underline{C}_\beta(x;\kappa_\beta); \bar{C}_\beta(x;\kappa_\beta)\right]$, with $\underline{C}_\beta(x;\kappa_\beta) < m(x) < \bar{C}_\beta(x;\kappa_\beta)$. If $c \in \mathcal{I}_\beta(x;\kappa_\beta)$ at the time the borrower has an opportunity to prepay, the borrower stays put. Otherwise the borrower prepays and refinances (or moves):

- if $c \leq \underline{C}_\beta(x;\kappa_\beta)$, the household refinances or moves, prepays its mortgage and realizes a mark-to-market gain $1 - p\left(x, c\right)$;

- if $c \geq \bar{C}_\beta(x;\kappa_\beta)$, the household refinances or moves and prepays its mortgage at par.

The bounds of the inaction region $\mathcal{I}_\beta(x;\kappa_\beta)$ satisfy, for all x:

$$v\left(x, \bar{C}_\beta(x;\kappa_\beta)\right) = v\left(x, m(x)\right) + \kappa_\beta \tag{9}$$

$$v\left(x, \underline{C}_\beta(x;\kappa_\beta)\right) = v\left(x, m(x)\right) + \kappa_\beta - 1 + p\left(x, \underline{C}_\beta(x;\kappa_\beta)\right) \tag{10}$$

The above reasoning will be relevant for all refinancing decisions since we impose $\tilde{\kappa}_\lambda > 0$, and for moving decision whenever the random net moving cost $\tilde{\kappa}_\psi$ is strictly positive. Instead, when a moving opportunity arises, if the realization κ_ψ of the random net moving cost $\tilde{\kappa}_\psi$ is negative, equations (9) and (10) cannot be satisfied; in that case, the inaction region for moving decisions is empty, $\mathcal{I}_\psi(x;\kappa_\psi) = \emptyset$, and it is optimal for the borrower to move irrespective of the value of the mortgage coupon.

4.5 Long run distribution, refinancing and moving hazard rates

In our model, the yield gap is $z_t = z\left(x_t, c_t\right) := c_t - m\left(x_t\right)$. The mortgage trades at a premium (resp. discount) whenever $z_t > 0$ (resp. $z_t < 0$). Imagine that we track an economy with a continuum of Danish households, all financing their house via FRMs. One can characterize the long-run distribution over interest rates and coupons $f(x,c)$, defined via:

$$f(x,c)dcdx := \lim_{t \to +\infty} \frac{1}{t} \int_0^t \mathbb{1}\left(x_t \in [x, x+dx]; c_t \in [c, c+dc]\right) dt. \tag{11}$$

This ergodic density satisfies the KF equation, for $c \neq m(x)$

$$0 = \mathcal{L}^* f(x,c) - \sum_{\beta=\lambda,\psi} \beta F_\beta \left(v(x,c) - v\left(x, m(x)\right) + \max\left(0, 1 - p(x,c)\right)\right) f(x,c), \tag{12}$$

where $\mathcal{L}^*$ is the adjoint of the operator $\mathcal{L}$[25] and F_β is the cumulative distribution function for the random net cost $\tilde{\kappa}_\beta$. In equation (12), the term $\mathcal{L}^* f(x,c)$ encodes changes in the

[25]For any twice continuously differentiable function f, the adjoint is defined via $\mathcal{L}^* f(x) := -\frac{d}{dx}\left[\mu(x) f(x)\right] + \frac{d^2}{dx^2}\left[\frac{\sigma^2(x)}{2} f(x)\right]$.

household distribution related to changes in the state x_t, while the second term is an exit term associated with prepayments, either due to refinancings ($\beta = \lambda$) or moves ($\beta = \psi$), occurring at intensity β times the probability $F_\beta\left(v(x,c) - v\left(x, m(x)\right) + \max\left(0, 1 - p(x,c)\right)\right)$ that the net cost $\tilde{\kappa}_\beta$ is sufficiently low for the option to be exercised.

Let $h(z), h_\lambda(z), h_\psi(z)$ be the model-implied prepayment, refinancing and moving hazards, as a function of the yield gap, that an econometrician would estimate, if she had an infinite time-series data available. One can characterize such hazard rates using the ergodic density f of our dynamic system:

$$h_\beta(z) = \beta \frac{\int F_\beta\left(v\left(x, z + m(x)\right) - v(x, m(x)) + \max\left(0, 1 - p\left(x, z + m(x)\right)\right)\right) f\left(x, z + m(x)\right) dx}{\int f\left(x, z + m(x)\right) dx}$$

$$h(z) = h_\lambda(z) + h_\psi(z).$$

4.6 Calibration

We compute the equilibrium recursively using the finite-difference method described in Section IA.1.2. The state variable x_t summarizes the term structure of interest rates and follows an Ornstein-Uhlenbeck process

$$dx_t = -\eta(x_t - \bar{x})dt + \sigma dZ_t, \tag{13}$$

with short rate $r(x) = \max(0, x)$. This "shadow rate" specification allows nominal interest rates to remain non-negative while accommodating the prolonged low-rate environment observed in Denmark during our sample period.

Table 3 shows the calibrated model parameters. When possible, parameters are calibrated from institutional features or existing empirical estimates; the remaining parameters are chosen to match moments of Danish refinancing and moving behavior.

We set the effective tax rate on mortgage interest to $\theta = 33\%$ (Gruber, Jensen and Kleven, 2021) and the subjective discount rate to $\rho = 5\%$, following Agarwal, Driscoll and Laibson (2013) and Berger et al. (2025).

Refinancing costs are log-normally distributed with mean $\bar{\kappa}_\lambda = 0.80\%$ and standard deviation $\sigma_\lambda = 0.50\%$. The mean is chosen to match the refinancing costs documented by Andersen et al. (2020), who estimate refinancing costs of approximately 0.80% of the outstanding balance for a representative Danish FRM.[26] Following the same paper, refinancing opportunities arrive according to a Poisson process with annual intensity $\lambda = 33\%$, corresponding to their estimated quarterly inattention probability of 92%.[27]

We set the mean net moving cost to $\bar{\kappa}_\psi = 0$, reflecting the conservative assumption that, on average, the benefits and costs of moving offset each other. The remaining moving parameters, ψ and σ_ψ, are jointly calibrated to match (i) the average annual moving rate among Danish FRM borrowers (3.2%) and (ii) the sensitivity of the moving hazard to the yield gap for positive yield gaps.[28] The second target exploits the model prediction that the moving hazard is increasing in the yield gap whenever the par prepayment option is in the money. The resulting calibration yields $\psi = 5.5\%$ and $\sigma_\psi = 10\%$.

Finally, we estimate the parameters of our shadow rate model $(\eta, \bar{x}, \sigma)$ by maximum likelihood using monthly Danish 10-year government bond yields from January 1987 through December 2019. For each parameter vector, we invert the model to recover the shadow-rate series that exactly matches observed 10-year yields; this series is then used as input in the maximum likelihood estimation. The resulting estimates imply an ergodic shadow rate of 0.51% and a half-life of 7.6 years; the parameter estimates are reported in Table 3.

4.7 Model results

4.7.1 Model vs. data: refinancing and moving hazard rates

The left panel of Figure 5 plots the equilibrium mortgage rate $m(x)$ together with the refinancing inaction region $\mathcal{I}_\lambda(x; \bar{\kappa}_\lambda) = [\underline{C}_\lambda(x; \bar{\kappa}_\lambda), \bar{C}_\lambda(x; \bar{\kappa}_\lambda)]$ as a function of the 10-year government yield.[29] The figure illustrates that households refinance whenever mortgage

[26] Andersen et al. (2020) model refinancing costs as $\kappa(\phi) = 3{,}000 + \max(0.002\phi, 4{,}000) + 0.001\phi$, where ϕ denotes the mortgage principal. For the average FRM in our sample (approximately DKK 1,000,000), this specification implies refinancing costs of roughly DKK 8,000, or 0.80% of the outstanding balance.

[27] See Andersen et al. (2020), Model 3, which incorporates inattention through an "asleep" probability and abstracts from psychological costs, focusing exclusively on monetary refinancing costs, as in our calibration.

[28] Specifically, we target a slope of $0.0158 + 0.0303 = 0.046$ using monthly moving rates, i.e. a slope of $12 \times 0.046 = 0.55$ using annual moving rates; see Table 2, column 2.

[29] The inaction region is evaluated at the mean refinancing cost $\bar{\kappa}_\lambda$. Since $\bar{\kappa}_\psi = 0$, the corresponding moving inaction region is empty when evaluated at the mean moving cost, although households do not always move because moving costs are stochastic.

coupons become sufficiently high or sufficiently low relative to prevailing market rates, corresponding to par prepayments and discounted buybacks, respectively.

Figure 6 provides a complementary representation by plotting the probability of refinancing (left panel) and moving (right panel), conditional on receiving a refinancing or moving opportunity. Refinancing exhibits a narrow inaction region around zero yield gaps, where the benefits of adjustment are insufficient to offset refinancing costs. The corresponding transition is considerably smoother for moving decisions because moving costs are substantially more dispersed than refinancing costs.

The right panel of Figure 5 reports the refinancing and moving hazards implied by the model. Random refinancing costs smooth the sharp optimal stopping thresholds, generating the U-shaped refinancing hazard observed in the data: refinancing activity is low near zero yield gaps and rises sharply for both sufficiently positive and sufficiently negative yield gaps, consistent with Figure 4. The rise at positive gaps is the standard par-refinancing response. The rise at *negative* gaps is where the Danish contract departs from the U.S. S-curve, along which refinancing activity essentially vanishes once coupons fall below market rates (Berger et al., 2021): here the buyback right lets households repurchase discounted debt and reset to a higher coupon, par-priced mortgage, and mortgage-interest deductibility makes doing so attractive.

The model also predicts that the moving hazard varies much less with the yield gap than the refinancing hazard, again consistent with the data, and the two sides of that hazard are shaped by different features of the contract. Conditional on receiving a moving opportunity, the household chooses whether to move or stay, and moving resets the coupon to the prevailing market rate. At *positive* yield gaps, this reset is valuable, and progressively more so as the gap widens. Thus households accept progressively higher moving-cost draws and dispersion in moving costs turns this into a smooth upward slope. The slope is sustained for higher yield gaps rather than plateauing quickly, though it does eventually flatten, as the exercise probability approaches 1.[30]

[30]The plateau in Fonseca and Liu (2024) arises for a different reason, reflecting a different timing assumption. In our model, refinancing and moving opportunities arrive through separate Poisson processes, so a household receiving a moving opportunity compares moving with remaining in its current home; because refinancing in place is not available at that moment, the benefits from the yield gap reset does not cancel from the comparison and the moving hazard slopes upward until the exercise probability saturates. In a framework where households instead choose simultaneously among staying, refinancing, and moving, the benefits from the yield gap reset accrues on both the moving and refinancing branches and cancels

At *negative* yield gaps, the flatness is the direct consequence of the buyback right: a mover can repurchase the mortgage at its market value rather than settling at par, so relocation no longer forfeits the embedded capital gain. The value of future tax deductions from resetting to a higher coupon reinforces this, raising the maximum moving cost households will absorb, but the mobility result does not depend on it—settling at market rather than par substantially dampens the lock-in effect, even absent tax-benefits. This stands in sharp contrast to the U.S., where prepayment at par means moving forfeits the gain and mobility falls as rates rise—a contrast we make quantitative in Section 4.10 by adding the buyback right to U.S. mortgages and isolating its effect on moving.

Overall, the model closely reproduces the refinancing and moving hazard rates documented in Section 3.

4.7.2 Key economic mechanisms: fixed costs and tax incentives

We next discuss the key economic mechanisms embedded in the model that generate refinancing and moving hazards consistent with those observed in the data. To clarify these mechanisms, we rely on comparative statics. Figure 7 presents comparative statics with respect to the average refinancing cost, $\bar{\kappa}_\lambda$, and the mortgage interest tax rate, θ.

The left panel illustrates a simple intuition: higher refinancing costs widen the region of inaction. This expansion is asymmetric. The lower threshold, $\underline{C}_\lambda(x;\bar{\kappa}_\lambda)$ — below which borrowers optimally repurchase their mortgages at a discount — shifts more in response to increases in refinancing costs than does the upper threshold, $\bar{C}_\lambda(x;\bar{\kappa}_\lambda)$, above which borrowers prepay and refinance at par.

The right panel highlights the role of mortgage interest deductibility in shaping the lower boundary of the inaction region. A reduction in the tax rate θ lowers the present value of future interest deductions, thereby delaying the exercise of the buyback option and shifting $\underline{C}_\lambda(x;\bar{\kappa}_\lambda)$ downward. By contrast, the upper threshold, $\bar{C}_\lambda(x;\bar{\kappa}_\lambda)$, is largely insensitive to changes in the tax rate, reflecting the fact that par refinancing decisions are driven primarily by interest rate considerations rather than tax incentives.

Taken together, these comparative statics highlight two central mechanisms. First, the repurchase-at-market option mitigates mortgage lock-in by strengthening moving

once staying is dominated, so the propensity to move becomes independent of the gap—the plateau.

incentives when yield gaps are negative. This effect is intuitive: households that move while facing a negative yield gap can do so without forfeiting the capital gains embedded in their FRM.

Second, mortgage interest deductibility plays a key role in motivating discounted buybacks in Denmark. When yield gaps are negative, refinancing into a higher-coupon mortgage raises future interest deductions and thereby lowers the present value of lifetime tax liabilities. This mechanism closely parallels the trade-off theory of corporate leverage (Leland, 1994), in which firms balance the tax benefits of debt against expected distress costs. Analogously, households in our model trade off the tax advantages of higher mortgage interest payments against the fixed costs associated with mortgage buybacks.

4.8 Different beliefs over rate persistence

Our theory emphasizes the role of mortgage interest deductibility in generating incentives for borrowers to repurchase mortgages at a discount. An alternative explanation is that some households expect elevated interest rates to be less persistent than implied by market prices. To capture this mechanism, we relax the assumption of rational expectations and suppose borrowers perceive a faster speed of mean reversion than lenders. Specifically, let η_b and η_ℓ denote the perceived mean-reversion parameters of borrowers and lenders, respectively, with $\eta_b > \eta_\ell$.[31] Under this specification, in high rates environments, borrowers anticipate faster future declines in interest rates, increasing the attractiveness of discounted buybacks.

To illustrate the quantitative importance of this channel, we compare the benchmark model with homogeneous beliefs to a specification in which borrowers perceive the half-life of interest rates to be half as long as implied by market prices, i.e., $\eta_b = 2\eta_\ell$. As shown in Figure A-7, heterogeneous beliefs substantially increase discounted buyback activity but have negligible effects on equilibrium mortgage rates.

Empirically, both mechanisms are likely to operate: discounted buybacks may reflect households seeking to increase their tax shields, but also households who believe that

[31] Our framework is a special case of a heterogeneous-beliefs economy in which agents "agree to disagree" (Harrison and Kreps, 1978; Scheinkman and Xiong, 2003).

elevated interest rates will be temporary relative to market expectations. Discussions with a senior practitioner at a large Danish mortgage lender indicate that refinancing recommendations routinely combine after-tax cash-flow comparisons with assessments of future interest rates. In the case of upward conversions (replacing a low-coupon, discount-priced mortgage with a higher-coupon loan issued near par), advisors evaluate both the break-even horizon and the likelihood that borrowers will subsequently refinance into lower-coupon mortgages if rates decline. These institutional practices suggest that discounted buybacks are jointly driven by tax incentives, which affect after-tax borrowing costs, and expectations about future interest rates, which determine whether households view a higher-coupon mortgage as a temporary bridge until rates fall.

4.9 Alternative channels

In addition to the tax and belief-based mechanisms emphasized above, other economic forces may also contribute to discounted mortgage buybacks in Denmark.

One such mechanism arises from the contribution fee charged by Danish mortgage institutions. Because this fee depends on the loan-to-value (LTV) ratio at origination, refinancing a discounted mortgage into a smaller face value, par-priced, loan reduces both the outstanding principal and the future contribution fee. Although this channel may strengthen incentives to refinance, we abstract from it for three reasons. First, the contribution fee varies only modestly with LTV: our estimates imply an increase of roughly 5 bps for every 10 p.p. increase in LTV. Second, modeling this channel would require introducing LTV as an additional state variable. Third, our baseline refinancing policy keeps the mortgage face value constant by allowing borrowers to extract the discount as cash, leaving the LTV ratio — and therefore the contribution fee — unchanged. For these reasons, we view the contribution-fee channel as a secondary force relative to the tax and belief-based mechanisms emphasized in our analysis.

A second mechanism is home equity extraction. Borrowers facing liquidity needs may refinance discounted mortgages to convert housing wealth into cash, since repurchasing debt below par while issuing new debt at par can generate immediate liquidity. Modeling this channel would require introducing risk-averse households, incomplete markets, idiosyncratic income risk, and endogenous savings so that refinancing decisions interact with consumption-smoothing motives. Instead, our baseline model features risk-neutral households without binding liquidity constraints. Accordingly, while home equity extraction might matter empirically, especially for financially constrained households, it lies outside the scope of the present analysis.

4.10 U.S. prepayable mortgage debt

As discussed in Section 2, Danish and U.S. fixed-rate mortgages share many contractual features, except that Danish borrowers may repurchase their mortgages at market value, whereas U.S. borrowers may only prepay at par.[32] We now use our model to study how introducing a Danish-style repurchase-at-market option into U.S. fixed-rate mortgages would affect household behavior and equilibrium mortgage rates.

4.10.1 Introducing a repurchase-at-market option in the U.S.

We compare two institutional environments. The first corresponds to the current U.S. mortgage market, in which borrowers can prepay only at par; equilibrium objects are denoted by the subscript "us". The second introduces a Danish-style repurchase-at-market option while assuming that realized gains from discounted repurchases are taxed as capital gains; equilibrium objects are denoted by "us∗". Let θ_i denote the marginal tax rate on mortgage interest deductions and θ_g the capital gains tax rate.[33] The corresponding borrower value functions satisfy

$$
\begin{aligned}
(\rho+\alpha)v_{\mathrm{us}}(x,c) &= \alpha + (1-\theta_i)c + \mathcal{L}v_{\mathrm{us}}(x,c) \\
&\quad + \sum_{\beta=\psi,\lambda} \beta\mathbb{E}\left[\min\left[0, v_{\mathrm{us}}\left(x, m_{\mathrm{us}}(x)\right) + \tilde{\kappa}_\beta - v_{\mathrm{us}}(x,c)\right]\right]
\end{aligned} \tag{14}
$$

[32] The Danish and U.S. mortgage systems differ along several additional dimensions, but these differences are unlikely to materially affect the quantitative conclusions of this section. For instance in Denmark, mortgage institutions retain borrower credit risk and charge a separate credit contribution fee (bidrag) to compensate for this risk. In the U.S. agency FRM market, credit risk is borne by the housing agencies, which charge a guarantee fee (G-fee) embedded in the mortgage coupon. Importantly, in both systems the interest cash flows received by mortgage investors exclude compensation for borrower credit risk, which instead accrues to the mortgage institution or agency.

[33] Following the discussion in Section 2.4, we assume that gains from discounted mortgage repurchases would be treated as capital gains under U.S. tax law.

$$
\begin{aligned}
(\rho+\alpha)v_{\text{us}*}(x,c) = \alpha + (1-\theta_i)c + \mathcal{L}v_{\text{us}*}(x,c) \\
+ \sum_{\beta=\psi,\lambda} \beta\mathbb{E}\left[\min\left[0, v_{\text{us}*}\left(x, m_{\text{us}*}(x)\right) + \tilde{\kappa}_\beta - v_{\text{us}*}(x,c)\right.\right. \\
\left.\left. -(1-\theta_g)\max\left(0, 1-p_{\text{us}*}\left(x,c\right)\right)\right]\right]
\end{aligned} \tag{15}
$$

Relative to Denmark, the current U.S. model simply removes the repurchase-at-market option. The counterfactual reinstates this option while recognizing that discounted repurchases generate taxable capital gains, unlike in Denmark. Mortgage prices satisfy

$$
\begin{aligned}
(r(x)+\alpha)p_{us}(x,c) &= c + \alpha + \mathcal{L}p_{us}(x,c) \\
&+ \sum_{\beta=\lambda,\psi} \beta\left[1-p_{us}(x,c)\right]\mathbb{P}\left(v_{us}(x,c) > v_{us}(x, m_{us}(x)) + \tilde{\kappa}_\beta\right)
\end{aligned} \tag{16}
$$

$$
\begin{aligned}
(r(x)+\alpha)p_{\text{us}*}(x,c) &= c + \alpha + \mathcal{L}p_{\text{us}*}(x,c) \\
&+ \sum_{\beta=\lambda,\psi} \beta\min\left[0, 1-p_{\text{us}*}(x,c)\right]\mathbb{P}\left(v_{\text{us}*}(x,c) > v_{\text{us}*}(x, m_{\text{us}*}(x)) + \tilde{\kappa}_\beta\right. \\
&\left. -(1-\theta_g)\max\left[0, 1-p_{\text{us}*}(x,c)\right]\right)
\end{aligned} \tag{17}
$$

As in the baseline model, we abstract from borrower default because agency MBS investors are protected by GSE guarantees and therefore view default as economically equivalent to prepayment.[34]

We estimate the shadow-rate process (13) by maximum likelihood using U.S. 10-year Treasury yields over the 1987-2019 period and calibrate the remaining parameters following the procedure in Section 4.6, using the evidence in Fonseca and Liu (2024) for moving hazards and Berger et al. (2025) for refinancing hazards.[35] The calibration,

[34]We also abstract from borrower heterogeneity in prepayment or credit risk. In practice, discounted repurchases in the U.S. would likely be exercised disproportionately by borrowers with higher attention rates, higher financial literacy or with strong credit quality, since refinancing would remain subject to the same underwriting standards as any newly originated mortgage. This dynamic adverse selection would affect the default and prepayment behavior of the remaining mortgage pool, and therefore MBS prices and equilibrium mortgage rates. We abstract from this mechanism in our paper. For a structural analysis of dynamic adverse selection, endogenous refinancing, and mortgage pricing in the U.S. mortgage market, see Berger et al. (2024).

[35]Specifically, we continue to assume $\bar{\kappa}_\psi = 0$ and we discipline the moving parameters ψ and σ_ψ so as to match (a) the empirical moving rate at zero yield gap, equal to 7% per year, and (b) the slope of moving rates w.r.t. the yield gap, equal to 0.95, corresponding to the midpoint of the range of slope estimates [0.69-1.20] in Fonseca and Liu (2024). Attention rate λ is directly taken from Berger et al. (2025), whereas we

summarized in Table 3, sets the mortgage interest deduction to 22% and the capital gains tax rate to 15%.[36]

Figure 8 compares the implied refinancing and moving hazards under the two regimes. Without the repurchase-at-market option, refinancing occurs only for positive yield gaps and moving hazards decline sharply as households become locked into below-market-rate mortgages. Introducing the option has only a modest effect on refinancing at negative yield gaps because the tax benefits of discounted repurchases are attenuated by lower mortgage interest deductions and taxation of capital gains. In contrast, moving hazards become much less sensitive to negative yield gaps, substantially mitigating mortgage lock-in.

4.10.2 How much would mortgage rates increase by?

The model allows us to quantify the effect of the repurchase-at-market option on equilibrium mortgage rates. In our calibration, we have

$$\mathbb{E}\left[m_{\mathrm{us}*}(x_t)\right] - \mathbb{E}\left[m_{\mathrm{us}}(x_t)\right] = 0.20\%,$$

where the expectation is taken over the ergodic density of the term structure state variable x. In other words, introducing the option raises mortgage rates by only 20 bps on average. This increase is modest because the repurchase-at-market feature is not a true option from the lender's perspective: borrowers repurchase their mortgages at fair market value, so exercise does not directly transfer value from investors. Instead, the option eliminates the occasional capital gains that investors realize under the current U.S. system when moving borrowers prepay discounted mortgages at par. Because such events are infrequent, their effect on equilibrium mortgage rates is limited.

Figure 9 shows that the pricing effect varies substantially with the level of interest rates. When rates are low, the option increases mortgage rates by roughly 50 bps. Low-

assume average refinancing costs of around 1.5%, broadly consistent with estimates discussed in Agarwal, Driscoll and Laibson (2013) or Berger et al. (2025).

[36]The 22% marginal income tax rate applies to households with taxable income between $100,800 and $211,400 in FY 2025, while 15% is the federal long-term capital gains tax rate for households with income below $553,850. We abstract from the additional complexity of itemization requirements and the $750,000 cap on deductible mortgage principal.

rate environments are typically associated with upward-sloping yield curves, making newly originated mortgages more likely to trade at a discount in the future. Under the current U.S. system, investors benefit when these discounted mortgages are prepaid at par following a move; allowing repurchases at market value eliminates these gains and therefore raises mortgage rates. By contrast, when interest rates are high, the yield curve is typically downward sloping, so newly originated mortgages are unlikely to trade below par in the future. The repurchase-at-market option then has little value, and its effect on mortgage rates is negligible.

4.10.3 How valuable is the buyback option to households?

We compute two mortgage spreads that measure the private value of the repurchase-at-market option, taking as given the equilibrium mortgage rates prevailing under each contractual regime. The first values the option for the existing stock of borrowers, while the second measures its value to new borrowers at mortgage origination.

We begin with the *status-quo population*. We define w as the constant increase in the mortgage coupon that leaves households drawn from the no-buyback equilibrium indifferent, on average, between the current U.S. mortgage contract and one that includes a repurchase-at-market option. Formally, w solves

$$\iint v_{\mathrm{us}}(x,c) f_{\mathrm{us}}(x,c) dx dc = \iint v_{\mathrm{us}*}(x,c+w) f_{\mathrm{us}}(x,c) dx dc, \tag{18}$$

where f_{us} denotes the ergodic density in the no-buyback equilibrium. We hold this distribution fixed because the exercise asks how much the status-quo population would be willing to pay for the alternative contract.

We find an equivalent mortgage spread of $w = 65$ bps/year. This spread provides a money-metric measure of the private value households attach to the buyback option. The value arises both because discounted repurchases can increase the expected present value of mortgage interest deductions and because the option relaxes mortgage lock-in, allowing households to accept positive-net-benefit moving opportunities that they would otherwise optimally forgo. The willingness to pay is particularly large because the status-quo mortgage stock places substantial probability mass on negative yield gap states, precisely those in which the buyback option is most valuable.[37]

We next measure the value of the option to *new borrowers*. Define the at-origination equivalent spread w_o as the uniform coupon surcharge that leaves households originating new mortgages indifferent, on average, between the two contracts. It solves

$$\int v_{\text{us}}\left(x, m_{\text{us}}(x)\right) f^o_{\text{us}}(x)dx = \int v_{\text{us}*}\left(x, m_{\text{us}}(x) + w_o\right) f^o_{\text{us}}(x)dx, \tag{19}$$

where $f^o_{\text{us}}(x)$ denotes the ergodic distribution of new mortgage originations across interest-rate states in the no-buyback equilibrium.[38] We obtain $w_o = 43$ bps. This value is smaller than the 65 bps spread for the existing stock because new borrowers begin with at-market coupons, whereas the existing population consists largely of households already locked into below-market mortgages for whom the buyback option is especially valuable.

Both w and w_o are positive, implying that households are better off under the buyback contract even after accounting for the higher equilibrium mortgage rates associated with that contract. In this sense, the equivalent spreads measure households' willingness to pay for the repurchase-at-market option net of its equilibrium pricing effect. Although our model does not provide a full welfare analysis—households are risk neutral and mortgage decisions are isolated from broader consumption and housing choices—these equivalent mortgage spreads provide natural money-metric measures of the private value households assign to repurchase-at-market rights.

4.10.4 Alternative tax structures

Our baseline U.S. counterfactual assumes that mortgage interest remains tax deductible at rate θ_i, while capital gains realized from discounted mortgage repurchases are taxable at rate θ_g. We now consider two alternative tax regimes that help isolate the role played by these tax provisions.

[37] Numerically, in the no-buyback equilibrium, households spend on average $\iint_{\{(x,c):\, m_{\text{us}}(x)>c\}} f_{\text{us}}(x,c)dxdc = 75\%$ of the time at negative yield gaps.

[38] Formally, $f^o_{\text{us}}(x)$ is proportional to the ergodic prepayment hazard in state x, i.e.

$$f^o_{\text{us}}(x) \propto \sum_{\beta=\lambda,\psi} \int \beta F_\beta\big(v_{us}(x,c) - v_{us}(x, m_{us}(x)) + \max(0, 1 - p_{us}(x,c))\big) f_{us}(x,c)dc$$

What if discounted mortgage repurchases were tax exempt? First, suppose capital gains from discounted mortgage repurchases are tax exempt, as in Denmark. Within our framework, this counterfactual simply amounts to solving the model with $\theta_g = 0$.

The results are reported in Figure 8. Relative to the taxable-gains case, refinancing hazards become strictly positive for negative yield gaps and increase as the gap widens, reflecting the stronger incentive to realize untaxed capital gains. Moving hazards also increase modestly, by roughly 25-50 bps per year when yield gaps fall below -300 bps. Despite these behavioral changes, equilibrium mortgage rates remain virtually unchanged, increasing by only 21 bps on average relative to the current U.S. system.

What if U.S. households do not itemize? Second, we examine a tax regime without mortgage interest deductibility by setting $\theta_i = 0$, while continuing to assume that capital gains from discounted repurchases remain taxable. This counterfactual is motivated by the fact that, following the Tax Cuts and Jobs Act of 2017, only about 10% of U.S. taxpayers itemize deductions and therefore benefit from the mortgage interest deduction. The results are also reported in Figure 8. Eliminating the deduction almost entirely removes refinancing at negative yield gaps, since households no longer benefit from replacing discounted low-coupon mortgages with newly originated higher-coupon mortgages. Nevertheless, moving hazards remain substantially higher than under the current U.S. mortgage contract, indicating that the repurchase-at-market option continues to mitigate mortgage lock-in even in the absence of mortgage interest deductibility. Equilibrium mortgage rates are on average 18 bps above those in the equilibrium without buybacks; the more modest increase in mortgage rates (relative to the counterfactual in which mortgage interest is taxable) stems from the reduction in moving hazards at negative gaps when mortgage interest is no longer taxable.

Interestingly, removing the mortgage interest deduction also strengthens household responses at positive yield gaps. When mortgage interest is deductible, the government effectively subsidizes interest payments, reducing households' exposure to differences between their existing mortgage coupon and prevailing market rates. Eliminating the deduction removes this subsidy, making households fully bear the coupon differential and thereby increasing both refinancing and moving incentives when market rates fall below existing mortgage rates. Put differently, mortgage interest deductibility attenuates the incentive to refinance or move at positive yield gaps, while constituting essentially the entire incentive to refinance discounted mortgages at negative yield gaps.

4.10.5 Neutralizing the pricing impact of the repurchase-at-market option

We then consider a simple modification of the prepayment rule that neutralizes the average effect of the repurchase-at-market option on equilibrium mortgage rates. Specifically, we allow borrowers to prepay at the minimum of (i) the market value of the mortgage and (ii) par plus a prepayment premium, where the premium is set so that the ergodic average mortgage rate coincides with that under the current U.S. contract (which is prepayable at par only). Intuitively, while the repurchase-at-market option removes the windfall to lenders associated with par prepayments when mortgages trade at a discount, the prepayment premium restores this value in expectation. Calibrating this premium within our model yields a value of 2.0% of outstanding principal. Under this contract, the average level of mortgage rates is unchanged, yet the state-contingent benefits of the repurchase-at-market option — most notably the mitigation of rate-induced lock-in — are preserved. This exercise highlights that the aggregate pricing impact of the option can be offset through modest adjustments to prepayment terms, without undoing its effects on household mobility.

4.10.6 Robustness

We assess the robustness of our estimate of the value of the repurchase-at-market option — 20 bps per annum on average in our baseline calibration — through a series of sensitivity analyses.

Figure 10 reports comparative statics for the ergodic average difference in equilibrium mortgage rates between contracts with and without the repurchase-at-market feature across alternative parameter values. The value of the option is primarily governed by two factors: the arrival intensity of moving opportunities and the dispersion of moving costs (and to a lesser extent the rate volatility). A higher arrival intensity increases moving rates uniformly, thereby raising the likelihood that move-related par prepayments occur when mortgages without the repurchase-at-market option trade at a discount. Similarly, greater dispersion in moving costs flattens the sensitivity of the moving hazard to the yield gap, increasing the probability that such prepayments occur in discount states. In both cases, the value of the repurchase-at-market option rises. Quantitatively, however, these effects remain moderate: even when the arrival intensity of moving opportunities increases by 25%, the ergodic average mortgage rate under the repurchase-at-market contract exceeds that under the current system by only 25 bps.

As a complementary exercise, we recalibrate the U.S. moving block to match the sensitivity of moving rates to the yield gap estimated by Fonseca and Liu (2024) either at the low end, or high end of their range, rather than at the midpoint of their range. Holding the zero-yield-gap moving hazard fixed at its baseline value and targeting their full-sample estimate of 0.69 requires greater dispersion in moving costs and raises the cost of the repurchase-at-market option from 20 bps to approximately 23 bps because it implies more moves at negative yield gaps; targeting their steeper post-2022 estimate of 1.20 instead lowers it to approximately 18 bps because it implies fewer moves at negative yield gaps. These results are consistent with the comparative statics above: the pricing effect is governed primarily by the hazard of moving opportunities and the dispersion of moving costs, and plausible recalibrations to the different estimates in Fonseca and Liu (2024) place the cost between roughly 18 and 23 bps without changing our conclusions.

A related question is whether the cost of the option depends on the treatment of home equity extraction at refinancing. In our baseline model, which features risk-neutral households and abstracts from liquidity motives, borrowers who refinance discounted mortgages keep the face value of their debt constant and extract the implied gains as cash. To assess the importance of this assumption, we solve an alternative specification in which refinancing is cash-neutral: households replace the existing mortgage with a new loan whose face value equals the market value of the old mortgage. Section IA.1.1 provides details of this alternative model. Recomputing equilibrium mortgage rates with and without the repurchase-at-market option yields an option value that remains essentially unchanged at 20 bps per annum.

As a last robustness exercise, Section IA.1.4 replaces our baseline one-factor shadow-rate term structure model with a two-factor specification in which the second factor captures stochastic interest-rate volatility.[39] The model is estimated using Treasury yields jointly with the Treasury Volatility Index (TYVIX), following the procedure described in

[39] We thank Dan Greenwald for making this suggestion.

Section IA.1.4. Re-estimating the counterfactual using this richer term structure model leaves our conclusions essentially unchanged: introducing a Danish-style buyback option into U.S. mortgages increases equilibrium mortgage rates by approximately 16 bps, compared with 20 bps under our baseline specification. This modest difference reflects the shorter estimation sample required by the availability of TYVIX data, which begins only in 2003, rather than the introduction of stochastic volatility itself.

Taken together, these results indicate that our conclusions are robust across a wide range of parameter values and modeling assumptions, and that introducing repurchase-at-market rights would increase equilibrium mortgage rates by a modest amount only.

5 Implementing buyback rights in the U.S.

This section outlines how a Danish-style buyback right could be implemented in the U.S. and compares it to the main alternatives, assumability and portability. We argue that buyback rights require no new infrastructure, only marginally alter the duration of prepayable fixed-rate mortgage debt, depend less on lender discretion, and are better suited to the realities of household mobility.

5.1 Buyback option in the U.S. mortgage market

Agency market. There are at least two ways to introduce repurchase-at-market rights within the existing agency mortgage framework.

A first approach would modify the prepayment provisions embedded in agency MBS contracts: a borrower exercising the repurchase option would retire the mortgage by paying the lower of par and the loan's market value, with the corresponding principal written off from the associated MBS pool and investors realizing the mark-to-market loss through reduced principal repayments. Because no secondary-market transaction occurs, the definition of "market value" must be transparent, objective, and standardized — for example, derived from observable prices of agency MBS with similar characteristics under a methodology specified ex ante by the GSEs or regulators. This approach would be simple to administer, requiring only modifications to prepayment and guarantee rules while leaving pooling, servicing, and trading infrastructure largely unchanged.[40] Unlike the Danish system, however, it would force all investors in the affected securities to realize losses whenever borrowers exercise the option.

A second approach would more closely mirror the Danish covered-bond system. A centralized registry would link each mortgage, via a unique identifier, to the agency MBS pool in which it resides. A borrower wishing to repurchase would transact through a broker or dealer, who would acquire in the secondary market securities of the specific pool in which the loan resides, in a quantity corresponding to the loan's outstanding principal; upon delivery, the mortgage would be extinguished and the principal retired from the pool. Because the borrower must deliver securities of the pool containing their own mortgage, there is no scope to select which bond to repurchase, exactly as in the Danish system. The repurchase price would thus be set directly by observed market transactions. This approach preserves the voluntary nature of mark-to-market realization — only investors who choose to sell realize losses — just as Danish repurchases are funded through secondary-market bond purchases rather than principal write-downs imposed on all bondholders. The main additional operational requirement is the registry itself, and a change in the rules governing the special purpose entities issuing MBS so as to allow the cancellation of notional related to mortgage buybacks.

Under both approaches, mortgages would continue to be originated, pooled, guaranteed, and serviced through the current agency framework. The first implementation emphasizes administrative simplicity; the second more faithfully reproduces the economic structure of the Danish system by relying on voluntary secondary-market transactions.[41]

[40] Implementing this approach would require revising the GSE guarantee from "timely payment of principal and interest" to a structure that preserves timely interest while allowing principal payments at market value. We thank Ed Golding for highlighting the analogy to REMIC structures: GSEs already guarantee securities whose principal repayment rules differ from simple par pass-through. Similar to the introduction of UMBS, credit risk transfer ("CRT") securities, or adjustments in guarantee fees, implementing repurchase-at-market rights for new agency mortgages would likely require regulatory action by FHFA to modify guarantee language and MBS contracts, but would not necessarily require congressional legislation.

[41] Our quantitative analysis abstracts from these implementation details and instead focuses on the economic consequences of granting borrowers the right to retire mortgage debt at market value. Because both approaches allow borrowers to capture the market value of their mortgage liabilities when rates rise, we expect our conclusions regarding household mobility, refinancing behavior, and equilibrium mortgage rates to apply under either implementation.

Jumbo market. In the jumbo segment, deposit-taking institutions frequently retain newly originated mortgages on their balance sheets as portfolio loans. When market rates rise above the mortgage coupon, borrowers could in principle offer to repurchase the mortgage at a discount: the loan's market value has fallen below par, so a discounted payoff may still exceed its value to the lender. In practice, however, portfolio mortgages are generally classified as held-for-investment ("HFI") and carried at amortized cost, so rising rates do not generate mark-to-market losses in reported earnings or regulatory capital. A discounted repurchase would crystallize part of the unrealized economic loss into a realized accounting loss — to the extent the repurchase price falls below carrying value net of loan-loss allowances — immediately reducing reported earnings and, potentially, regulatory capital ratios. Banks may therefore be reluctant to entertain discounted buybacks even when they are economically efficient ex ante. Reforming accounting and regulatory capital rules so that unrealized losses are recognized more transparently would reduce these barriers and facilitate repurchase-at-market provisions in the jumbo market.

5.2 Comparison with alternative mechanisms

Assumability and portability are the main alternatives for mitigating mortgage lock-in while preserving fixed-rate contracts. Assumable mortgages allow a home buyer to take over the seller's existing loan, whereas portable mortgages allow the borrower to transfer an existing mortgage to a new property.[42] Both mechanisms preserve existing mortgage contracts but require lender approval, re-underwriting, and additional operational steps at each transaction.

Discretion and price mismatch. The key advantage of repurchase-at-market rights is that they replace discretionary approval with a contractual right settled at an observable market price. Assumability changes the borrower and therefore requires lender consent and underwriting of the buyer. Portability changes the collateral and therefore

[42] Qualifying-assumption clauses exist in U.S. government-backed programs (FHA, VA, and USDA). Portability is institutionalized in both Canada and the U.K., with standard product offerings — including port-and-increase, port-and-decrease, and delayed-port variants — available at major lenders.

requires re-underwriting of the property, updated loan-to-value assessments, and lender approval.

More fundamentally, portability and assumability preserve the contractual terms of the existing mortgage rather than its economic value. As households' financing needs evolve over time, this distinction becomes increasingly important. Consider a homeowner with a $400,000 mortgage carrying a 3% coupon who purchases a new home requiring $600,000 of financing after market rates have risen to 7%. Under a buyback regime, the homeowner repurchases the existing mortgage at its market value (approximately $280,000), realizes the resulting $120,000 capital gain, and originates a new $600,000 first-lien mortgage at 7%.

Under portability, the existing $400,000 balance retains the 3% rate, but the additional $200,000 must be financed at prevailing market rates. In practice, this incremental borrowing generally takes the form of a second-lien mortgage, which is more costly and operationally more complex than first-lien financing. Under assumability, the original mortgage is transferred to the buyer rather than retained by the seller. Because house prices typically appreciate while mortgage balances amortize over time, the buyer will generally require additional financing at current market rates to complete the purchase, again typically through a second-lien mortgage. Moreover, while the seller may capture part of the value embedded in the below-market mortgage through a higher sale price, bilateral bargaining makes it unlikely that the seller will appropriate the full value of the embedded subsidy, leaving part of the surplus to the buyer.

Buyback rights avoid both problems. By allowing the homeowner to repurchase the existing mortgage at market value, they preserve the full economic value embedded in the mortgage while allowing the replacement loan to be originated as a single first-lien mortgage. The resulting capital gain remains with the moving household regardless of the size or direction of the move, making repurchase-at-market rights equally effective for upsizing, downsizing, and job-related relocation.

Revealed preference. The limited use of assumability illustrates the practical importance of these frictions. Consider for instance FHA and VA loans, which are contractually assumable, and for which the 2022–2023 rate increases made assumption more valuable than at any point in decades. Yet FHA assumptions totaled just 2,221 in 2022 and 3,825 in 2023, while VA assumptions were 308 and 2,244, respectively (Lerner, 2024; U.S. House of Representatives, Committee on Financial Services, 2024). With 7–8 million active FHA-insured loans outstanding, these volumes represent well under 0.05% of eligible mortgages annually.[43]

The Danish market provides a sharper test, because assumability and buyback rights coexist there, allowing us to observe which mechanism households actually use when both are available. Using Danish registry data (see Section 3.1), we identify assumed mortgages with two complementary approaches: mortgages that persist from one year to the next but become associated with a new borrower identification number, and — to rule out administrative reassignment of loan identifiers — cases in which property ownership changes while the mortgage retains the same coupon rate and maturity year. Both methods yield nearly identical counts: fewer than 2,500 assumed mortgages from 2020 to 2023, against approximately 100,000 discount FRM repurchases in 2022 and again in 2023. When both mechanisms are contractually available, households choose buybacks over assumptions by roughly two orders of magnitude.

Taken together, these comparisons suggest that contractual assumability alone is unlikely to provide a broad solution to mortgage lock-in. Unlike assumability and portability, repurchase-at-market rights neither require bilateral bargaining nor depend on collateral substitution, instead operating through the existing mortgage payoff and origination process.

Borrower sophistication. A common critique is that repurchase-at-market rights would primarily benefit sophisticated borrowers. The comparison, however, runs in the opposite direction. Assumability and portability require discretionary approvals, bilateral bargaining, and, in many cases, complex multi-lien financing, whereas repurchase-at-market rights are contractually self-executing at observable market prices. Differences in borrower sophistication would no doubt affect take-up, as they do for refinancing generally (Andersen et al., 2020), but such frictions apply to all three mechanisms and are arguably smallest under repurchase-at-market rights. For moving households in par-

[43] Assumption activity was similarly negligible in earlier periods: between 2001 and 2019, only about 104,000 FHA loans were assumed, with annual assumption rates falling from 0.27% of active loans in 2001 to roughly 0.05% by 2006 (Park, 2022, exhibits 5–6) — though for most of that period falling rates left the assumption option out of the money.

ticular, settlement at the lower of par and market value occurs automatically at closing, requiring no borrower initiative.

Institutional infrastructure. Repurchase-at-market rights build on existing mortgage payoff and origination infrastructure. Because investors already price and hedge prepayment risk, introducing a repurchase-at-market right simply replaces move-related par prepayments of discounted mortgages with market-value settlements, modestly increasing equilibrium mortgage rates (see Section 4.10). By contrast, portability and assumability require additional institutional infrastructure to support collateral transfers, borrower substitutions, and junior-lien financing.

5.3 ARMs vs. FRMs

Finally, one alternative for eliminating lock-in is adjustable-rate mortgages, which index payments to market rates and thus carry no embedded capital gains to forfeit. Whatever the merits of ARMs — for reducing lock-in, lowering borrowing costs, or improving monetary policy transmission — we do not view them as a realistic solution for the U.S. at this time. Over 85 percent of U.S. mortgage borrowers hold fixed-rate products, and the 30-year FRM is deeply embedded in American housing finance. Rather than prescribe a different mortgage type, we take households' preferences over interest rate exposure as given (Auclert, 2019) and ask how to reduce the frictions embedded in the contracts they have chosen.

6 Conclusion

Our paper shows that mortgage contract design plays a central role in shaping how households respond to interest rate shocks. In the Danish fixed-rate mortgage system, the ability to repurchase debt at market value fundamentally alters refinancing and moving behavior, weakening the rate-induced lock-in that characterizes the U.S. mortgage market. We document these patterns empirically and develop an equilibrium model that highlights how buyback rights and tax incentives jointly govern household decisions.

Our counterfactual analysis demonstrates that introducing a Danish-style buyback option into U.S. fixed-rate mortgages would substantially reduce lock-in and preserve household mobility, with only modest effects on equilibrium mortgage pricing. The strength of these effects depends on institutional details, particularly the tax treatment of mortgage interest and capital gains from debt forgiveness. More broadly, our findings emphasize that liability-side contract features are an important margin through which interest rate risk is distributed between households and lenders. Designing mortgage contracts that allow households to actively manage the market value of their liabilities with limited frictions can meaningfully alter the transmission of interest rate shocks, improve the functioning of housing and mortgage markets, and enhance household mobility.

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Table 1: Summary statistics for homeowners

	2010			2023			Pooled		
	ARM	FRM	NM	ARM	FRM	NM	ARM	FRM	NM
Mortgage characteristics									
Face value (in ,000)	1,286	874		1,667	1,315		1,393	1,113	
Original Maturity (in years)	29.03	27.36		28.87	27.01		28.85	26.85	
Coupon (%)	2.73	5.00		0.39	1.95		0.74	3.00	
Coupon gap (%)	-2.27	0.00		-3.61	-2.05		-2.11	0.23	
Issuance yield (%)		5.29			2.18			3.31	
Yield gap (%)		0.10			-2.73			0.38	
Simple averages									
Prepayment rate (in %)	9.37	24.48		10.26	17.48		12.60	21.22	
Refi rate (in %)	4.89	17.53		2.80	10.77		6.09	14.31	
Moving rate (in %)	3.64	2.88	3.60	4.14	3.32	4.64	4.39	3.31	4.16
Value weighted averages									
Prepayment rate (in %)	8.94	29.45		10.02	20.77		12.86	24.19	
Refi rate (in %)	4.64	23.28		3.17	14.34		6.48	18.08	
Moving rate (in %)	3.56	2.83		4.13	3.26		4.36	3.38	
Counts									
Count (in ,000)	528	581	342	523	606	350	8,151	7,489	4,703
Frequency (in %)	36.38	40.04	23.58	35.38	40.94	23.68	40.07	36.81	23.12

Note: The sample/data consists of the primary mortgages of all Danish households who own property. The statistics are computed for the years 2010, 2023 and for the full pooled sample. The frequency shows the percentage of each homeowner type among all homeowners. Prepayment, refinancing and moving rates are calculated for each individual homeowner type. Weighted averages are weighted by face value, while all homeowners are equally weighted for the simple averages. We use the abbreviation "NM" for homeowners with no mortgage.

Table 2: Moving and the (piece-wise linear) yield gap

	OLS		
	(1)	(2)	(3)
	Moving (pct)	Moving (pct)	Moving (pct)
Yield gap (p.p.)	-0.0115***	0.0158***	0.00851
	(0.00394)	(0.00488)	(0.00742)
Positive yield gap indicator	0.0140	0.0312***	0.0145
	(0.0142)	(0.00827)	(0.00972)
Yield gap × positive gap	0.0273**	0.0303***	0.0825***
	(0.0105)	(0.00529)	(0.00882)
Controls		X	X
Household FE			X
R-squared	0.00000894	0.000981	0.0410
Root MSE	5.659	5.508	5.427
Observations	64655942	61776297	61773308

Note: The table reports marginal effects on moving propensity of the yield gap, an indicator for a positive yield gap, and the interaction. For scaling purposes, the dependent variable is a binary indicator that takes the value 100 if the household moves. Column (1) reports estimates without additional controls. Column (2) adds a set of baseline controls following Fonseca and Liu (2024), including household age and age squared; household type (couple, single female, single male); log face value of the mortgage; log average monthly mortgage payment; remaining mortgage term fixed effects; month fixed effects; and year-by-municipality fixed effects. Column (3) adds household fixed effects to the regression of Column (2). Standard errors are double clustered at the issuance month–year and municipality levels and reported in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3: Model parameters

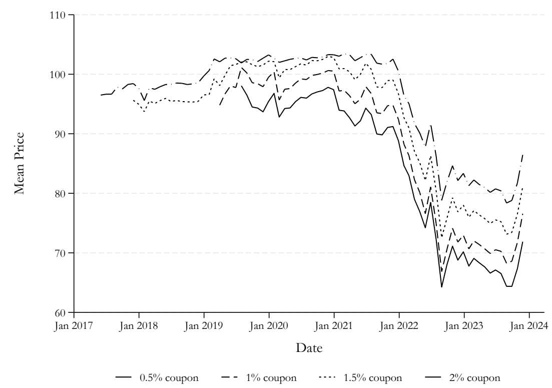
Parameter	Description	Value Denmark	Std. Error	Value U.S.	Std. Error
Borrowers and mortgage contract					
ρ	discount rate	0.05		0.05	
θ	marginal tax rate	0.33		0.22	
θ_g	capital gains' tax rate	0		0.15	
α	amortization rate	1/30		1/30	
Refinancing					
λ	refinancing opportunity hazard	0.33		0.23	
κ_λ	refinancing costs (mean)	0.008		0.015	
σ_λ	refinancing costs (s.d.)	0.005		0.005	
Moving					
ψ	moving opportunity hazard	0.055		0.14	
κ_ψ	net moving costs (mean)	0		0	
σ_ψ	net moving costs (s.d.)	0.10		0.23	
Term structure of interest rates					
$\bar{x}$	mean shadow rate	0.51%	0.04%	3.97%	0.06%
η	mean reversion speed	0.0917	0.0103	0.1195	0.0021
σ	conditional volatility	1.31%	0.01%	1.47%	0.04%

Note: This table reports parameters for our baseline model. Refinancing costs are assumed to be lognormally distributed, while net moving costs are assumed to be normally distributed. Parameters for the term structure of interest rates are estimated, with point estimates indicated in the column "value", alongside the standard errors of these estimates.

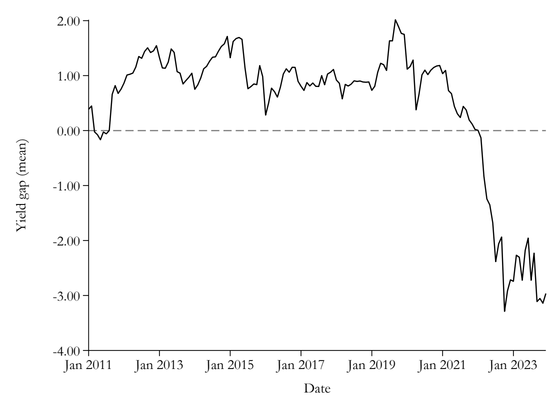
Figure 1: 30-year fixed-rate mortgages

(a): Mortgage rates

(b): Mortgage prices



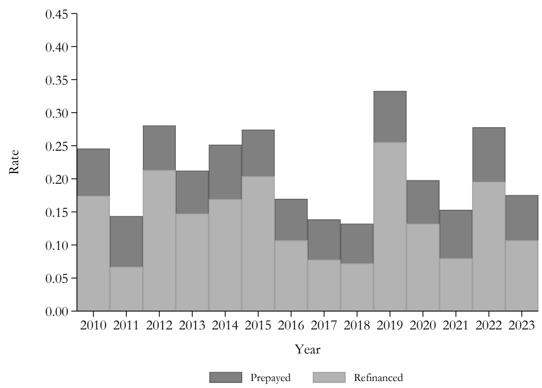
(c): Average yield gap over time



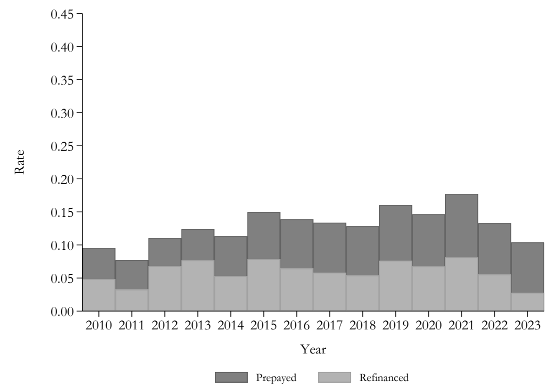
Note: Panel (a) shows the yield-to-maturity on long-term mortgage bonds funding newly originated fixed-rate mortgages, as provided by FinansDanmark. Panel (b) shows the market price of 30-year fixed-rate mortgage bonds maturing in 2050, carrying various fixed coupons, averaged across the seven largest mortgage institutions in Denmark: Nykredit, Totalkredit, LR, Jyske, Nordea, Realkredit Danmark, and BRF (source: Værdipapirscentralen). Panel (c) shows the average yield gap among households whose largest mortgage is a fixed-rate mortgage. The yield gap is defined as the difference between (i) the mortgage market yield prevailing when the household originated its mortgage and (ii) the contemporaneous mortgage market yield.

Figure 2: Prepayment and refinancing rates

(a): FRMs



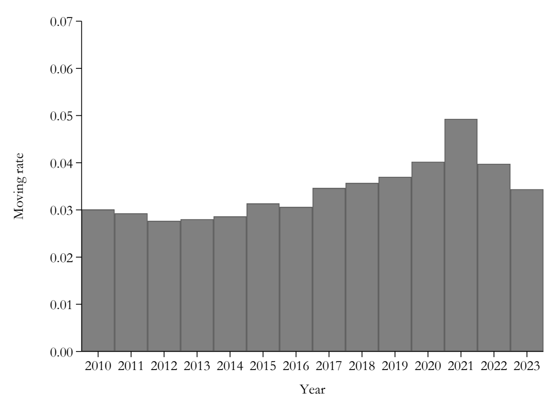
(b): ARMs



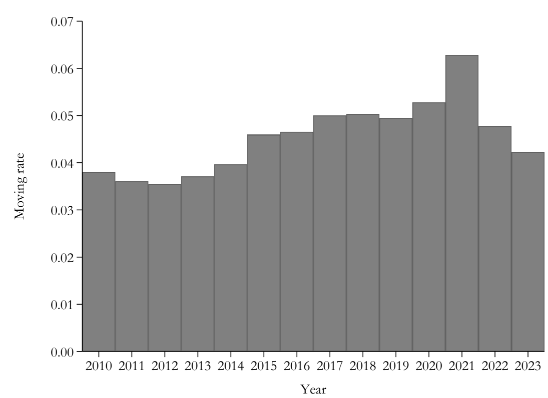
Note: Figure shows the primary mortgages of a given type prepaid or refinanced in a given year, as a fraction of the mortgage of that type outstanding at the beginning of the year. Panel (a) presents the data for fixed-rate mortgages (FRMs), while Panel (b) presents the data for adjustable rate mortgages (ARMs).

Figure 3: Moving rates

(a): FRMs



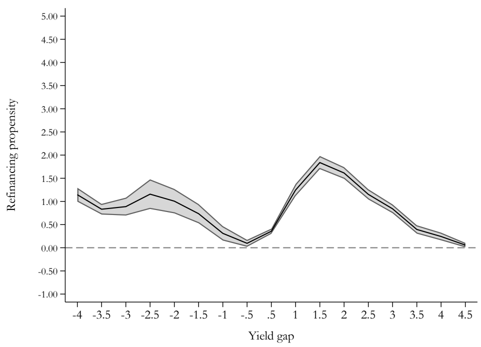
(b): ARMs



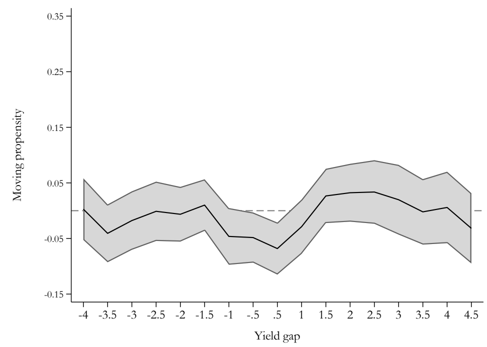
Note: The figure shows the aggregate moving rate among fixed-rate mortgage (FRM) holders (Panel (a)) and among adjustable-rate mortgage (ARM) holders (Panel (b)).

Figure 4: Refinancing and moving propensities

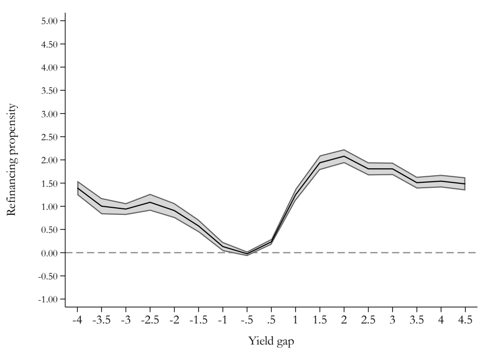
(a): Refinancing: No controls



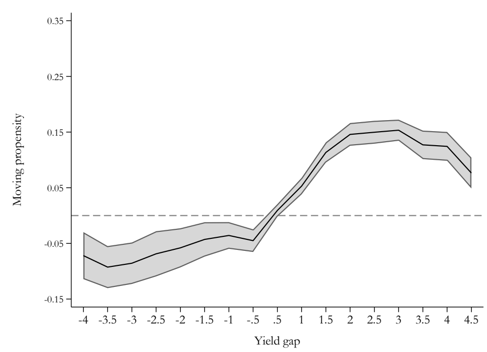
(b): Moving: No controls



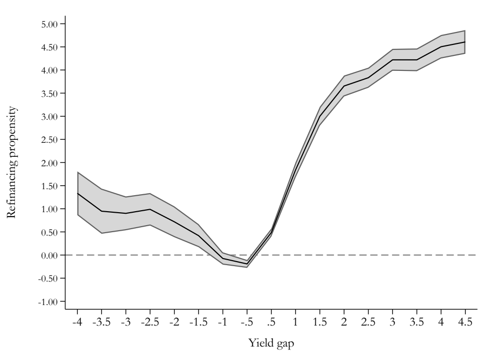
(c): Refinancing: Controls



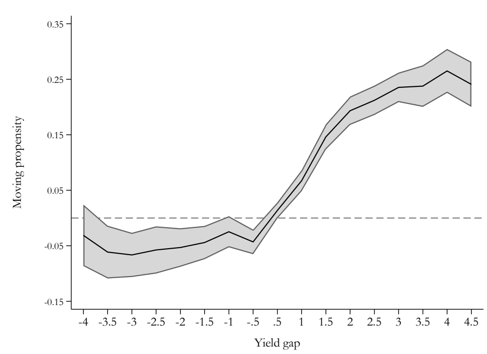
(d): Moving: Controls



(e): Refinancing: Household fixed effects



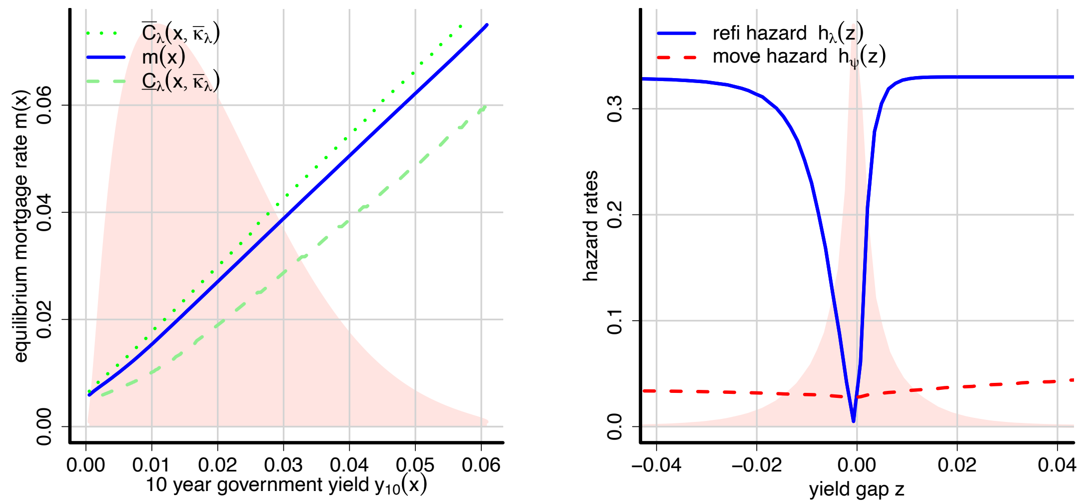
(f): Moving: Household fixed effects



Note: The left (right) column reports refinancing (moving) propensities as functions of yield gap dummies in 50 bps intervals. The first row reports estimates without controls. The second row controls for household age, household age squared, household type (couple, single female, single male), log mortgage face value, log average monthly mortgage payment, month fixed effects, year-by-municipality fixed effects, and remaining mortgage term fixed effects, following Fonseca and Liu (2024). The third row additionally includes household fixed effects. The displayed interval spans the 0.5th to the 99.5th percentile of the yield gap distribution, with the baseline category normalized to zero. Standard errors are double clustered by issuance month-year and municipality.

Figure 5: Equilibrium illustration

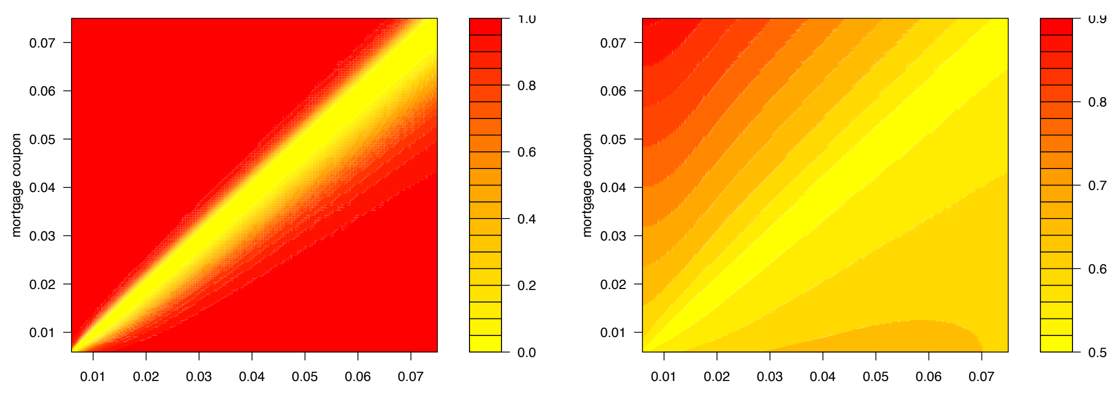
(a): Mortgage rate $m(x)$ **(b):** Hazard rates $h(z)$



Note: Left figure shows the equilibrium mortgage rate $m(x)$ and the boundaries $\underline{C}_\lambda(x;\bar{\kappa}_\lambda)$ and $\bar{C}_\lambda(x;\bar{\kappa}_\lambda)$ of the inaction region when the refinancing cost is equal to its mean $\bar{\kappa}_\lambda$, vs. the 10-year government yield $y_{10}(x)$. Right figure shows the implied refinancing, move and prepayment hazard rates, as a function of the yield gap z. In both figures, the pink shaded area shows the ergodic density of the variable on the x-axis.

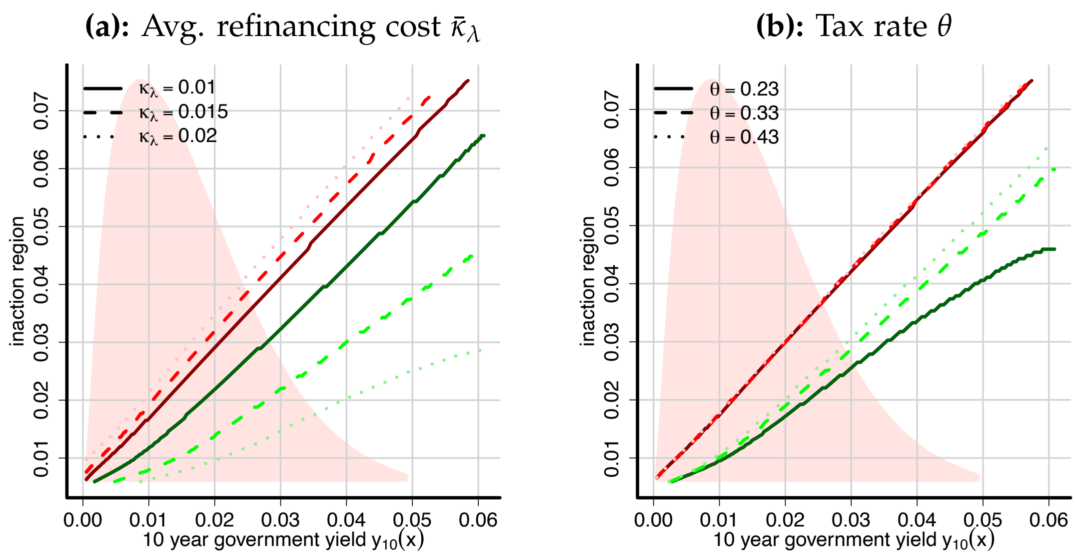
Figure 6: Exercise probabilities

(a): Refinancing probability **(b):** Moving probability



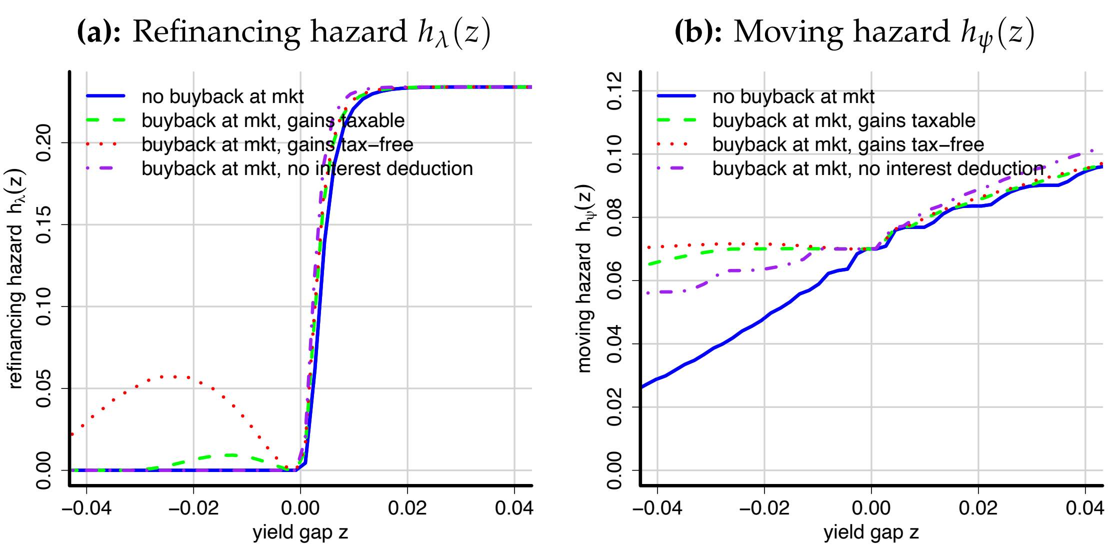
Note: Figures show the refinancing (left-hand side) and moving (right-hand side) probabilities for the baseline calibration of our model, conditional on getting an opportunity to refinance or move, as functions of (i) the current coupon c on the mortgage and (ii) the current mortgage market interest rate $m(x)$.

Figure 7: Comparative statics



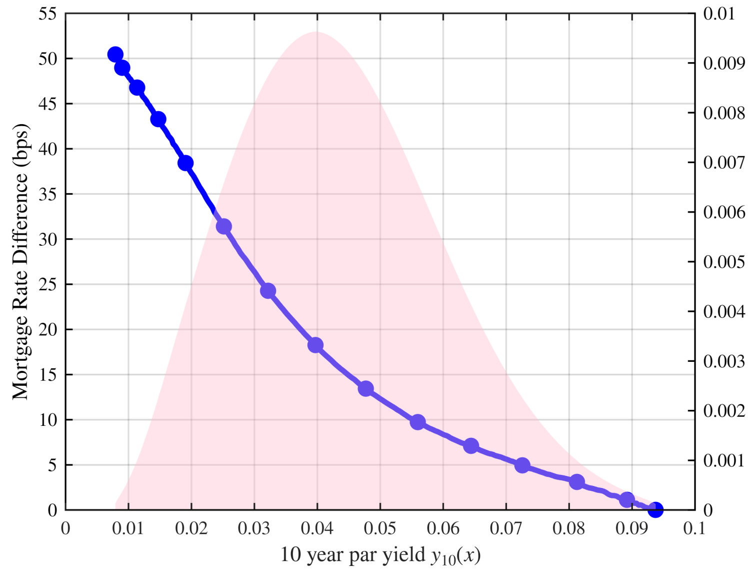
Note: Refinancing inaction region $\mathcal{I}_\lambda(x;\bar{\kappa}_\lambda)$ for varying values of the average refinancing cost $\bar{\kappa}_\lambda$ (left figure) and tax rate θ (right figure) evaluated when the realized cost is equal to $\bar{\kappa}_\lambda$, plotted as a function of the 10-year government yield $y_{10}(x)$. The upper boundary $\bar{C}_\lambda(x;\bar{\kappa}_\lambda)$ is represented in red, while the lower boundary $\underline{C}_\lambda(x;\bar{\kappa}_\lambda)$ is represented in green.

Figure 8: U.S. FRMs: with vs. without buyback option



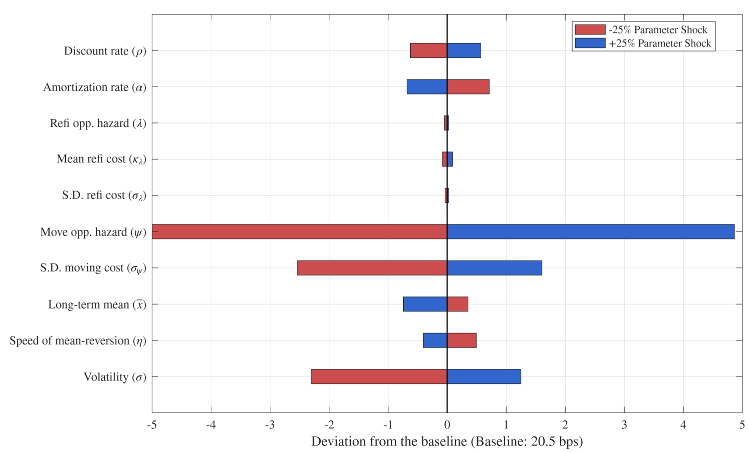
Note: Left (resp. right) figure shows the implied refinancing (resp. moving) hazard rates, as a function of the yield gap z, for FRMs without a repurchase-at-market option (solid blue), with the option with capital gains taxes on discount repurchases (dash green), with the option with capital gains non-taxable (dotted red), and with the option under taxable gains and no mortgage interest deduction (dash-dotted purple).

Figure 9: Effect of repurchase-at-market option on U.S. mortgage rates



Note: The blue dotted line shows $m_{\mathrm{us}*}(x) - m_{\mathrm{us}}(x)$, i.e. the difference in U.S. equilibrium mortgage rates (in bps) between (a) the contract with the buyback option and (b) the contract without it. The pink shaded area shows the ergodic density of the 10-year government yield $y_{10}(x)$.

Figure 10: Sensitivity analysis of repurchase-at-market option on U.S. mortgage rates



Note: This figure illustrates the sensitivity of the effect of the repurchase-at-market option on equilibrium mortgage rates to parameter variations. The bars plot the deviation in the average mortgage rate difference between the two contracts relative to the benchmark calibration. Blue (red) bars represent the results with a 25% increase (decrease) in the specified parameter, holding all other parameters constant.

Internet Appendix

A Danish Fix for U.S. Mortgage Lock-in?

David Berger Jaehun Jeong Julie Marx Maria Victoria Olesen
Fabrice Tourre

July 16, 2026

A Theory and numerical analysis

IA.1.1 Extension: no cash-out upon discounted buybacks

We revisit an assumption in our baseline model of Section 4.1: when refinancing or moving, the household is assumed to maintain the original mortgage balance and extracts home equity whenever the mortgage trades at a discount. We now consider an alternative behavior. Suppose that, upon refinancing or moving, the household instead chooses to conduct a cash-neutral transaction. That is, if the mortgage is trading at a discount when the opportunity to refinance or move arrives, the household reduces the face value of the new mortgage so that the transaction requires no net cash outlay. Under this alternative assumption, the household's problem becomes:

$$v(x,c) = \inf_{a \in \mathcal{A}} \mathbb{E}_{x,c}\left[\int_0^{+\infty} e^{-\int_0^t (\rho+\alpha)ds + a_s \sum_{\beta=\lambda,\psi} \ln\min(1,p(x_{s-},c_{s-}))dN_s^\beta} \left(\left((1-\theta)c_t^{(a)}+\alpha\right)dt \right.\right.$$
$$\left.\left. + a_s \sum_{\beta=\lambda,\psi} \kappa_\beta dN_s^\beta\right)\right],$$

$$\text{s.t.} \qquad dc_t^{(a)} = \left(m(x_t) - c_{t-}^{(a)}\right) a_t \left(\sum_{\beta=\lambda,\psi} dN_t^{(\beta)}\right)$$

This formulation makes it clear that the mortgage debt face value jumps discretely whenever buy-backs are done at a discount to par. The corresponding HJB equation for households' value function is

$$(\rho+\alpha)v(x,c) = \alpha + (1-\theta)c + \mathcal{L}v(x,c) +$$
$$\sum_{\beta=\lambda,\psi} \beta\mathbb{E}\left[\min\left[0, \min\left(1, p(x,c)\right)\cdot v(x,m(x)) + \tilde{\kappa}_\beta - v(x,c)\right]\right] \quad \text{(B-1)}$$

Consequently, the lower bound of the inaction region $\underline{C}_\beta(x;\kappa_\beta)$, which was (10) in the baseline, is now modified to:

$$v(x,\underline{C}_\beta) = p(x,\underline{C}_\beta)\cdot v(x,m(x)) + \kappa_\beta \quad \text{(B-2)}$$

The ergodic density $f(x,c)$ is governed by the modified KF equation as below:

$$0 = \mathcal{L}^* f(x,c) - \sum_{\beta=\lambda,\psi} \beta F_\beta \Big(v(x,c) - \min(1, p(x,c)) \cdot v(x, m(x)) \Big) f(x,c) \tag{B-3}$$

The aggregate hazard rates are now calculated as:

$$h_\beta(z) = \beta \frac{\int F_\beta \Big(v(x, z+m(x)) - \min(1, p(x, z+m(x))) \cdot v(x, m(x)) \Big) f(x, z+m(x)) dx}{\int f\,(x, z+m(x))\, dx}, \quad \beta = \lambda, \psi$$

$$h(z) = h_\lambda(z) + h_\psi(z).$$

Finally, mortgage prices follow the usual martingale condition (7).

IA.1.2 Equilibrium computation

IA.1.2.1 Notation

Since we assume a univariate process for the term structure state variable x_t, and since we assume that $r(\cdot)$ is monotone, one can introduce the variable x^*, defined as the value of the state x that was prevalent the last time a household took on a new mortgage: $m(x^*) := c$. For numerical calculations, we find it convenient to transform our state vector from (x,c), to (x,x^*). We implement a finite difference scheme to compute the functions (v,p) at $n \times n$ discrete points $\left(x_i, x_j^*\right)$ of the state space, for $1 \leq i,j \leq n$. Our discrete points are equally spaced by Δ_x. In order to calculate $v(x,x^*)$ and $p(x,x^*)$, we will look for a stationary solution to time-dependent functions $v^{(k)}(x,x^*)$, $p^{(k)}(x,x^*)$ (where k represents the iteration step) obtained iteratively via a false transient algorithm. We note $v_{i,j,k} = v^{(k)}(x_i, x_j^*)$ the borrower value function at iteration k, and use similar notation for mortgage prices. We note $m_{i,k} = m^{(k)}(x_i)$ the mortgage rate at iteration k, when the term structure state variable is x_i. We start with arbitrary chosen values $\left(v_{i,j,0}\right)_{i,j\leq n}$ and $\left(p_{i,j,0}\right)_{i,j\leq n}$, as well as a mortgage rate function $(m_{i,0})_{i\leq n}$. We define the forward, backward and centered difference approximations of $\partial_x v$ at iteration k as follows:

$$\partial_x v^b_{i,j,k} := \frac{v_{i,j,k} - v_{i-1,j,k}}{\Delta_x} \qquad \partial_x v^f_{i,j,k} := \frac{v_{i+1,j,k} - v_{i,j,k}}{\Delta_x} \qquad \partial_x v^c_{i,j,k} := \frac{v_{i+1,j,k} - v_{i-1,j,k}}{2\Delta_x}.$$

The finite difference approximation of $\partial_x v$ at step k will then be implemented using an upwinding scheme as follows:

$$\partial_x v_{i,j,k} := \mathbf{1}_{\{\mu_{x,i}<0\}} \partial_x v^b_{i,j,k} + \mathbf{1}_{\{\mu_{x,i}\geq 0\}} \partial_x v^f_{i,j,k},$$

where we have used the notation $\mu_{x,i} := \mu(x_i)$. We use a similar finite difference approximation of $\partial_x p$ at step k. Lastly, for both v and p, the finite difference approximation of $\partial_{xx}\phi$ (for $\phi = v$ or $\phi = p$) at iteration k will then be:

$$\partial_{xx}\phi_{i,j,k} := \frac{\phi_{i+1,j,k} + \phi_{i-1,j,k} - 2\phi_{i,j,k}}{\Delta_x^2}.$$

IA.1.2.2 Borrower value function

The discretization of equation (6) leads to a system of equations in the $n \times n$ unknown $\left(v_{i,j,k}\right)_{i,j\leq n}$:

$$\frac{v_{i,j,k} - v_{i,j,k-1}}{\Delta_t} + (\rho + \alpha)\, v_{i,j,k} = \alpha + (1-\theta) m_{j,k-1} + \sum_{\ell \in \{i-1,i,i+1\}} L_{i,\ell} v_{\ell,j,k}$$
$$+ \sum_{\beta=\lambda,\psi} \beta \int \min\left[0, v_{i,i,k-1} + \kappa_\beta - \max\left(0, 1 - p_{i,j,k-1}\right) - v_{i,j,k-1}\right] dF_\beta(\kappa_\beta) \quad \text{(B-4)}$$

This system of $n \times n$ equations, with unknown elements $v_{i,j,k}$ for $1 \leq i,j \leq n$, can be encoded in matrix form:

$$\left[\left(\frac{1}{\Delta_t} + \rho + \alpha\right) I - L\right] \vec{v}_k = \frac{1}{\Delta_t}\vec{v}_{k-1} + \alpha\vec{1} + (1-\theta)\vec{m}_{k-1} + \vec{o}_{k-1},$$

where the $n^2 \times 1$ vector $\vec{v}_k$ has entry $v_{i,j,k}$ in row $i + (j-1)n$, where I is a square $n^2 \times n^2$ identity matrix, where the $n^2 \times 1$ vector $\vec{1}$ has entries 1 at each row, where the $n^2 \times 1$ vector $\vec{m}_{k-1}$ has entry $m_{j,k-1}$ in all rows $i + (j-1)n, i \in \{1, ..., n\}$, where the $n^2 \times 1$ vector $\vec{o}_{k-1}$ has entry $\sum_{\beta=\lambda,\psi} \beta \int \min\left[0, v_{i,i,k-1} + \kappa_\beta - \max\left(0, 1 - p_{i,j,k-1}\right) - v_{i,j,k-1}\right] dF_\beta(\kappa_\beta)$ in row $i + (j-1)n$, and where the $n^2 \times n^2$ matrix L is block-diagonal, where each of the n sub-blocks have dimension $n \times n$ and are identical and equal to L_x. The $n \times n$ matrix L_x is the discrete state counterpart to the Feynman-Kac operator $\mathcal{L}$. It is a tri-diagonal matrix encoding the dynamic evolution of x_t. Its diagonal elements ($L_{x,i,i}$) and off-diagonal terms ($L_{x,i,i-1}$ and $L_{x,i,i+1}$) are the following:

$$L_{x,i,i} = -\left(\frac{|\mu_{x,i}|}{\Delta_x} + \frac{\sigma_{x,i}^2}{\Delta_x^2}\right) \qquad L_{x,i,i-1} = -\frac{\min(0,\mu_{x,i})}{\Delta_x} + \frac{\sigma_{x,i}^2}{2\Delta_x^2} \qquad L_{x,i,i+1} = \frac{\max(0,\mu_{x,i})}{\Delta_x} + \frac{\sigma_{x,i}^2}{2\Delta_x^2}$$

IA.1.2.3 Mortgage prices

For given value function $\left(v_{i,j,k-1}\right)_{i,j\leq n}$ at step $k-1$, we can compute the optimal moving and refinancing strategies of the borrower. In particular, one can determine when the borrower prepays (either at par, or at a discount), via:

$$\pi_{i,j,k-1}^{\beta} := \Pr\left(v_{i,j,k-1} > v_{i,i,k-1} + \tilde{\kappa}_\beta - \max\left(0, 1 - p_{i,j,k-1}\right)\right),$$

where $\pi_{i,j,k-1}^{\beta}$ is the probability that the borrower prepays (when $\beta = \lambda$) or moves (when $\beta = \psi$). The discretization of equation (7) leads to a system of equations in the n^2 unknown $\left(p_{i,j,k}\right)_{i,j\leq n}$, which can be written

$$\frac{p_{i,j,k} - p_{i,j,k-1}}{\Delta_t} + \left(r_i + \alpha + \sum_{\beta=\lambda,\psi} \beta \pi_{i,j,k-1}^{\beta}\right) p_{i,j,k} = \alpha + m_{j,k-1} + \sum_{\ell\in\{i-1,i,i+1\}} L_{i,\ell}\, p_{\ell,j,k} + \sum_{\beta=\lambda,\psi} \beta \pi_{i,j,k-1}^{\beta} \min\left(1, p_{i,j,k-1}\right), \quad \text{(B-5)}$$

where $r_i := r(x_i)$. This system of n^2 equations, with unknown elements $p_{i,j,k}$ for $1 \leq i, j \leq n$, can be encoded in matrix form:

$$\left[\left(\frac{1}{\Delta_t} + \alpha\right) I + R + \sum_{\beta=\lambda,\psi} \beta \Pi_{k-1}^{\beta} - L\right] \vec{p}_k = \frac{1}{\Delta_t} \vec{p}_{k-1} + \alpha \vec{1} + \vec{m}_{k-1} + \sum_{\beta=\lambda,\psi} \beta \Pi_{k-1}^{\beta} \min\left(\vec{p}_{k-1}, \vec{1}\right), \quad \text{(B-6)}$$

where the $n^2 \times 1$ vector $\vec{p}_k$ has entry $p_{i,j,k}$ in row $i + (j-1)n$, where Π_{k-1}^{β} is a square $n^2 \times n^2$ diagonal matrix with entry $\pi_{i,j,k-1}^{\beta}$ in row (and column) $i + (j-1)n$, and where

R is a square $n^2 \times n^2$ diagonal matrix with entry $r(x_i)$ in row (and column) $i + (j-1)n$, for all $1 \leq j \leq n$. Once we have computed mortgage prices at iteration k, we can update equilibrium mortgage rates, via identity (8).

IA.1.2.4 Ergodic density

The discretization of the dynamic system (x_t, x_t^*) can then be encoded via an $n^2 \times n^2$ matrix Λ, which encodes both (i) state transitions driven by the exogenous process x_t, and (ii) (endogenous) prepayments leading to changes in the state variable x_t^*. The ergodic density of the dynamic system follows equation (12) is then a vector $\vec{f}$ that is an eigen-vector of the matrix Λ', associated with the eigen-value zero, and which integrates to 1, i.e.:

$$\Lambda' \vec{f} = \vec{0} \qquad \vec{f} \cdot \vec{1} \Delta_x^2 = 1. \tag{B-7}$$

IA.1.3 Interest rate process estimation

In this section, we provide details of the estimation of the interest rate process for the Danish and U.S. term structure of interest rates. Imagine that the short term rate is $r(x_t) = \max(0, x_t)$, where x_t follows a Vasicek process:

$$dx_t = -\eta_x (x_t - \bar{x})\, dt + \sigma_x dZ_t.$$

The price of a T-maturity bullet bond with coupon c is by definition equal to

$$P(x, T; c) := \mathbb{E}_x \left[\int_0^T e^{-\int_0^t r(x_s)ds} c dt + e^{-\int_0^T r(x_s)ds} \right].$$

The T-maturity spot yield is then equal to $y_T^*(x) := -(1/T) \ln P(x, T; 0)$. The function $P(x, t; c)$ satisfies the standard PDE

$$\begin{aligned} r(x)P(x,t;c) &= c - \eta_x (x - \bar{x})\, \partial_x P(x,t;c) + \frac{\sigma_x^2}{2} \partial_{xx} P(x,t;c) - \partial_t P(x,t;c) \\ P(x,0;c) &= 1 \end{aligned}$$

Assume now that we have discretized the state variable x on a grid spaced by Δ_x, and that the infinitessimal operator has also been discretized, with associated intensity matrix L_x. Denote $R := \text{diag}(r(x_i))$, the price vector $\vec{P}(t;c)$ encodes the price of the coupon bond at each state x_i, and it solves

$$(R - L_x)\vec{P}(t;c) = c\vec{1} - \partial_t \vec{P}(t;c)$$
$$\vec{P}(0;c) = \vec{1},$$

which admits the analytic solution

$$\vec{P}(t;c) = \exp\left((L_x - R)t\right)\vec{1} + c(R - L_x)^{-1}\left[I - \exp\left((L_x - R)t\right)\right]\vec{1}$$

Given an empirical time series $\{y^*_{T,t}\}_{t=1,\ldots,n_t}$ of T-year spot rates, one can use our solution method to retrieve the shadow state x_t that solves $\ln P(x_t, T; 0) = -Ty^*_{T,t}$. Once we have recovered the time-series of shadow short rates $\{x_t\}_{t=1,\ldots,n_t}$, it is straightforward to compute the likelihood of this sequence of shadow rates, since the increments of x_t are normally distributed.

To end this section, we remind the reader of the definition of the T-maturity par yield $y_T(x)$: it is defined as the coupon of a T-maturity fixed rate bond that is trading at par at time of issuance, when the term-structure state variable is equal to x. In other words, the T-maturity par yield must satisfy $P(x, T; y_T(x)) := 1$.

IA.1.4 Regime-switching volatility in the shadow-rate model

The counterfactual analysis of Section 4.10 prices the repurchase-at-market option in a single-factor shadow-rate model, estimated by maximum likelihood as described in Section IA.1.3. This appendix assesses the robustness of that exercise to a richer description of interest-rate dynamics. We augment the single latent factor with a two-state, regime-switching stochastic volatility, and discipline the volatility process with the CBOE Treasury-note volatility index (TYVIX), estimating the system jointly on the 10-year U.S. Treasury yield and TYVIX using a simulation-based Bayesian procedure.

IA.1.4.1 Model and bond pricing

As in the main text, the instantaneous short rate is a shadow rate,

$$r_t = \max(0,\, x_t), \tag{B-8}$$

where the latent shadow rate x_t follows the Ornstein–Uhlenbeck process of (13), with a volatility that now depends on a latent regime s_t:

$$dx_t = -\eta\,(x_t - \bar{x})\,dt + \sigma_{s_t}\,dZ_t, \qquad s_t \in \{\ell, h\}. \tag{B-9}$$

Here $\eta > 0$ is the speed of mean reversion, $\bar{x}$ the long-run mean, and $\sigma_{s_t} \in \{\sigma_\ell, \sigma_h\}$ the regime-dependent volatility with $\sigma_h > \sigma_\ell$; setting $\sigma_\ell = \sigma_h$ recovers the single-factor process (13) of Section 4.6. The regime s_t is a continuous-time Markov chain with generator

$$\Lambda = \begin{pmatrix} -\lambda_{\ell h} & \lambda_{\ell h} \\ \lambda_{h\ell} & -\lambda_{h\ell} \end{pmatrix}, \qquad \Pi(\tau) = e^{\Lambda\tau}, \tag{B-10}$$

where $\lambda_{\ell h}, \lambda_{h\ell} > 0$ are transition *intensities* (rates per year) and $\Pi(\tau)$ is the matrix of transition probabilities over horizon τ. The parameter vector is $\Theta = (\eta, \bar{x}, \sigma_\ell, \sigma_h, \lambda_{\ell h}, \lambda_{h\ell})$, augmented by two measurement-error scales introduced below at the estimation stage. As in Section IA.1.3, the estimated dynamics serve as the pricing dynamics, so that the volatility regimes are pinned down jointly by the yield and by TYVIX.

Bond pricing is unchanged from Section IA.1.3 except that the diffusion now carries a regime label. We discretize the state space in the direction x as before, numerically solve for bond prices $P(x, s, t; c)$ as a function of the arbitrary coupon c, and define the 10-year (zero-coupon) yield via:

$$y^*_{10}(x, s) := -\frac{1}{10}\log P(x, s, 10; 0), \tag{B-11}$$

That is, $y^*_{10}(x, s)$ is the regime-conditional counterpart of the spot yield $y^*_{10}(x)$ of Section IA.1.3, computed conditional on the prevailing regime.

IA.1.4.2 From the model to TYVIX: the measurement equations

The two observables are the 10-year Treasury spot yield y_t and TYVIX v_t. The yield maps directly into the model through the pricing function, so its measurement equation is

$$y_t = y^*_{10}(x_t, s_t; \Theta) + \varepsilon^y_t, \qquad \varepsilon^y_t \sim \mathcal{N}(0, \sigma^2_y). \tag{B-12}$$

Mapping TYVIX requires more care, because TYVIX is a price volatility rather than a state variable. By construction, TYVIX is the (annualized) market-implied expected volatility of the 10-year Treasury futures price over the next 30 days,

$$\text{TYVIX}^2_t \;\approx\; \tfrac{1}{\Delta}\,\mathbb{E}_t\!\int_t^{t+\Delta} \sigma^2_F(u)\,du, \qquad \Delta := \tfrac{30}{365}, \tag{B-13}$$

where $\sigma_F(u)$ is the instantaneous volatility of the futures price. To connect σ_F to the model, apply Itô's lemma to the (log) bond price as a function of the shadow rate: locally $d\log P \approx (\partial_x \log P)\,dx_t$, so the price inherits a volatility $|\partial_x \log P|\,\sigma_{s_t}$. Defining the duration-like loading

$$D^{10}(x,s) := \partial_x \log P(x, s, 10; 0) = -10\partial_x y^*_{10}(x,s), \tag{B-14}$$

one finds that $\sigma_F(u) \approx D^{10}(x_u, s_u)\,\sigma_{s_u}$ is a good approximation to the futures-price volatility—the product of the bond's sensitivity to the state and the state's own volatility. Substituting and conditioning on the current regime gives the regime-switching expression

$$V^{10}(x_t, s_t) \approx \tfrac{1}{\Delta}\int_0^{\Delta} \sum_{j\in\{\ell,h\}} \Pi_{s_t j}(u)\big(D^{10}(x_t, j)\sigma_j\big)^2 du, \qquad \text{TYVIX}_t = 100\sqrt{V^{10}(x_t, s_t)}. \tag{B-15}$$

Because both x_t and s_t are highly persistent relative to the 30-day horizon Δ, the integral is well approximated by freezing the state at its current value,

$$V^{10}(x_t, s_t) \approx \big(D^{10}(x_t, s_t)\sigma_{s_t}\big)^2. \tag{B-16}$$

This persistence approximation removes the need to integrate the transition density over the option horizon at every likelihood evaluation and substantially accelerates the estimation, at negligible cost in accuracy. The TYVIX measurement equation is then taken in *levels* (percentage volatility), matching the model-implied price volatility directly to the observed index:

$$v_t = 100D^{10}(x_t, s_t)\sigma_{s_t} + \varepsilon_t^v, \qquad \varepsilon_t^v \sim \mathcal{N}(0, \sigma_v^2). \tag{B-17}$$

Equations (B-12) and (B-17) make the latent state (x_t, s_t) a nonlinear, non-Gaussian, regime-switching state-space system, with the yield identifying the level factor and the volatility index speaking to the volatility regime.

IA.1.4.3 Estimation and data

Because the regime-switching shadow-rate process makes the state-space system nonlinear and non-Gaussian, the exact-inversion maximum-likelihood approach of Section IA.1.3 is unavailable here. The process can no longer be inverted in closed form and its filtering distribution is non-Gaussian. The same obstacle rules out the Kalman filter, the standard tool in the shadow-rate literature (e.g., Wu and Xia, 2016). We therefore evaluate the likelihood with a *bootstrap particle filter*. The filter carries a swarm of $N = 2{,}000$ "particles", each a candidate value of the hidden state (x_t, s_t). Each month the particles are propagated through the model dynamics (a regime draw from $\Pi(\Delta)$ and an Ornstein–Uhlenbeck step with the regime's volatility) and re-weighted by how well they explain the observed yield and TYVIX through equations (B-12) and (B-17). The mean particle weight each month estimates that month's likelihood contribution, and the product across the T months gives an estimate of the joint likelihood $\widehat{p}(y_{1:T}, v_{1:T} \mid \Theta)$ that is *noisy but unbiased*.

The posterior is then obtained by *particle marginal Metropolis–Hastings* (PMMH; Andrieu, Doucet and Holenstein, 2010), a Bayesian MCMC algorithm in which the intractable likelihood in the Metropolis–Hastings acceptance ratio is replaced by the particle-filter estimate $\widehat{p}$. The pseudo-marginal property guarantees that, because $\widehat{p}$ is unbiased, the chain retains the *exact* posterior as its stationary distribution for any number of particles; more particles improve mixing rather than removing bias. We use a random-walk, one-at-a-time proposal, Gaussian priors with hard support bounds, and Robbins–Monro adaptation of the proposal scales during burn-in. A fresh filter is run at each proposal and the current likelihood is carried between accepted draws, as required for validity. The measurement-error scales σ_y, σ_v are estimated jointly with Θ.

TYVIX is available only from 2003, so, unlike the 1987–2019 single-factor estimation, the regime-switching model is estimated on monthly data from January 2003 to December 2019 ($T = 204$) using the 10-year constant-maturity Treasury yield and TYVIX (FRED series VXTYN).

IA.1.4.4 Estimation results

Table A-3 reports the baseline posterior. The chain is run for 5,000 iterations (1,000 burn-in); the reported posterior standard deviations and 95% intervals are the standard deviation and the 2.5–97.5 percentile (equal-tailed credible) interval of the post-burn-in draws.

The level factor is estimated with a mean-reversion speed $\eta \approx 0.17$ (a half-life of about four years) toward a long-run shadow rate $\bar{x} \approx 1.8\%$. The lower long-run mean relative to the single-factor U.S. estimate in Table 3 ($\bar{x} = 3.97\%$) reflects the shorter, lower-rate 2003–2019 window; the two regime volatilities, $\sigma_\ell \approx 1.1\%$ and $\sigma_h \approx 2.1\%$, straddle the single-factor estimate of 1.47%. The two volatility states are well separated, with $\sigma_h/\sigma_\ell \approx 1.8$. The transition intensities imply a mean duration of roughly $1/\lambda_{\ell h} \approx 3.1$ years in the low-volatility state and $1/\lambda_{h\ell} \approx 1.2$ years in the high-volatility state, and an ergodic probability of the high-volatility state of $\lambda_{\ell h}/(\lambda_{\ell h} + \lambda_{h\ell}) \approx 0.29$. The high-volatility regime probability is elevated over 2008–2013, consistent with the financial-crisis and post-crisis period.

The estimates are stable across a range of checks. Doubling the iterations (to 10,000) and raising the particle count (to 4,000) leaves the posterior essentially unchanged, confirming particle-independence and that the particle-filter noise is not biasing the posterior. The estimates are likewise insensitive to the random seed and to $\pm 10\%$ changes in the starting values. Fixing the transition intensities at the estimates of Kalimipalli and Susmel (2004), $\lambda_{\ell h} \approx 0.32$ and $\lambda_{h\ell} \approx 1.80$, leaves the remaining parameters close to the baseline, with only a small fall in the log-likelihood.

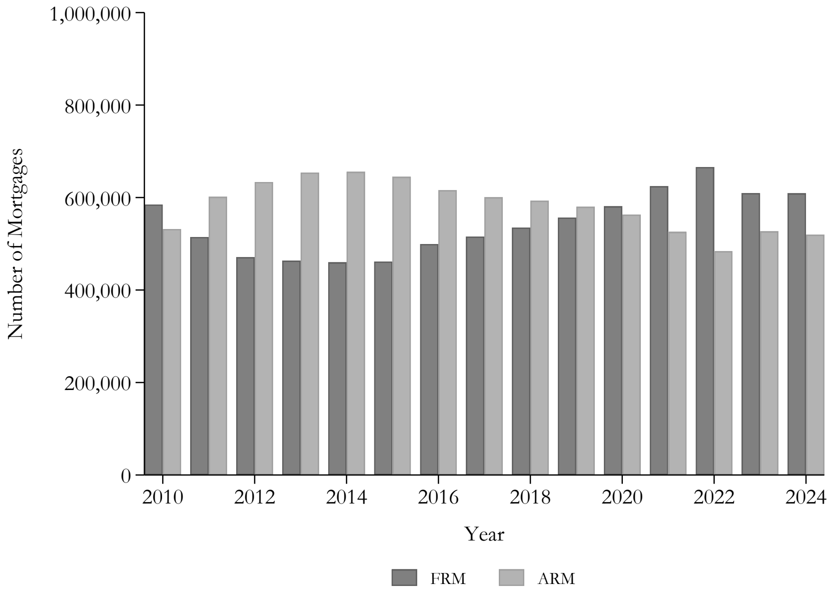
IA.1.4.5 Value of the repurchase-at-market option

Using the baseline regime-switching estimates, the ergodic-average difference in equilibrium U.S. mortgage rates between the contract with and without the repurchase-at-market option is approximately 16 bps, close to the single-factor baseline of 20 bps. The difference between these two numbers arises from the different sample periods used for estimation of one-factor and two-factor models, since data on the TYVIX is not available before 2003.

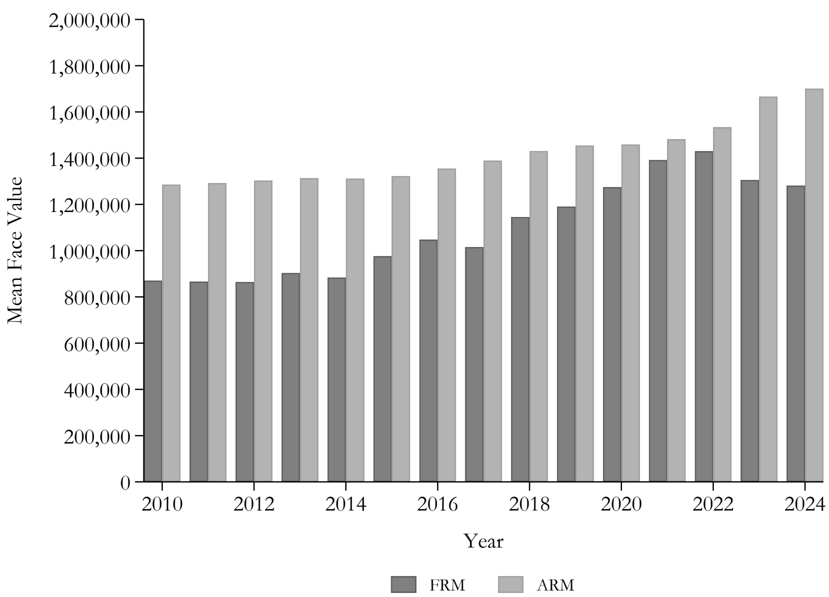
B Additional tables and figures

Figure A-1: FRMs vs. ARMs

(a): FRMs vs. ARMs outstanding

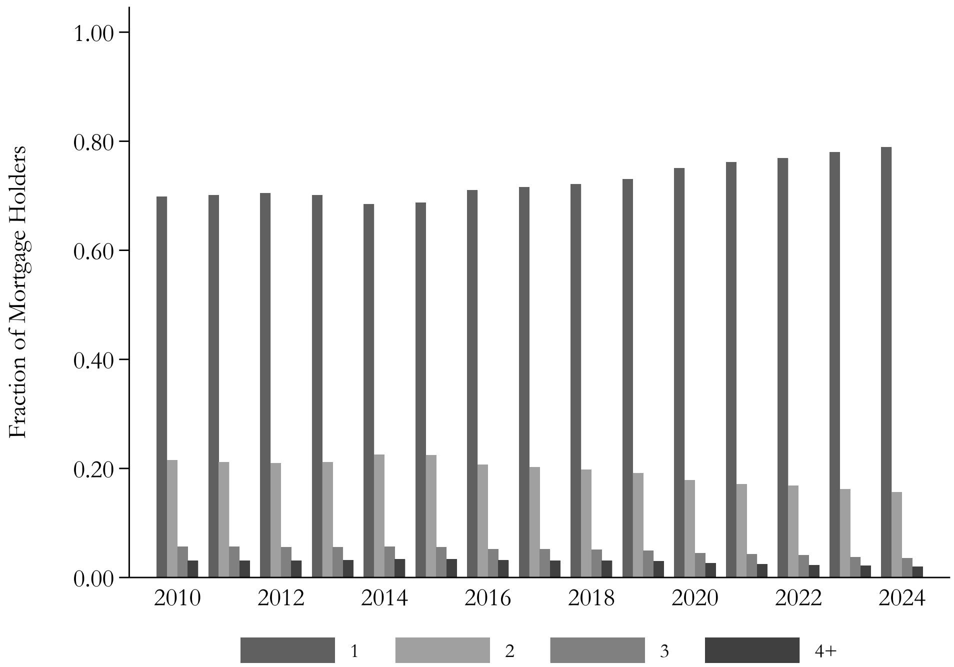


(b): FRMs vs. ARMs average face value



Note: Top figure shows the number of Danish households whose primary mortgage is either an ARM or an FRM at the beginning of each year. Bottom figure shows the average face value for households' primary mortgage, by type, in DKK.

Figure A-2: Number of mortgages, for households with at least one mortgage

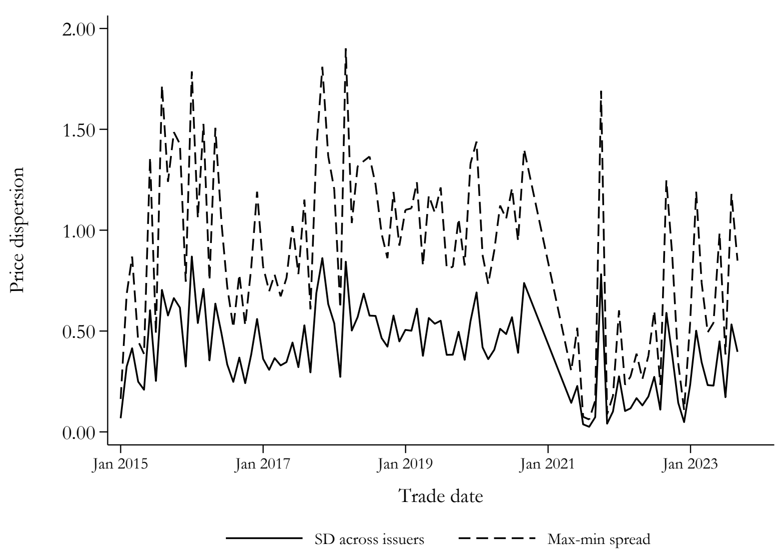


Note: Distribution of number of mortgages, showing the fraction of mortgage-indebted households with 1, 2, 3 or 4 + mortgages in the beginning of the year. The denominator consists of all households which have at least 1 mortgage in the beginning of the year.

Figure A-3: Mortgage bond prices across issuers

(a): Prices for 2% coupon bond

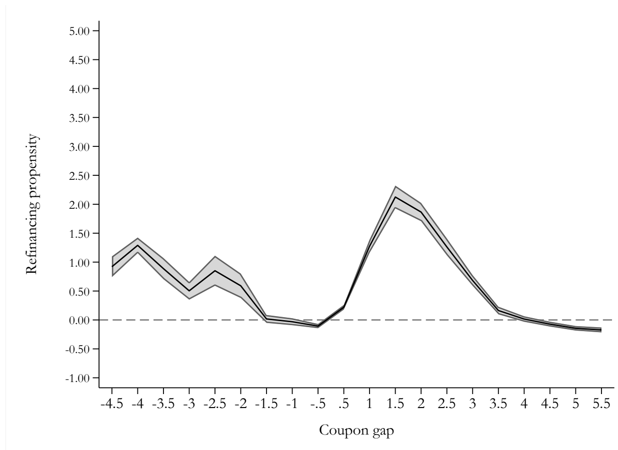
(b): Cross-sectional standard deviation over time



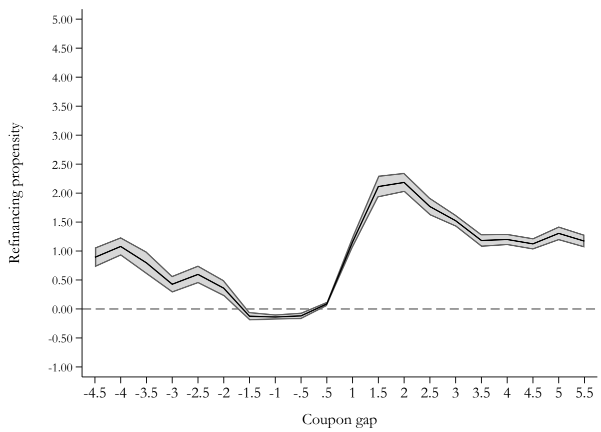
Note: Panel A shows the monthly average prices of mortgage bonds across the four largest Danish mortgage issuers: Nykredit, Nordea, Realkredit Danmark, and Jyske Realkredit. Panel B shows the cross-sectional dispersion in these issuer-level average prices over time. Specifically, for each month, we first compute the average bond price within each issuer. We then calculate the standard deviation of these issuer-level average prices as well as the difference between the highest and lowest issuer-level average price. Bond prices are not winsorized. Both panels are based on fixed-rate mortgage bonds with a 2% coupon and a remaining maturity of 30–35 years. Source: Værdipapirscentralen.

Figure A-4: Refinancing propensities vs. coupon gaps

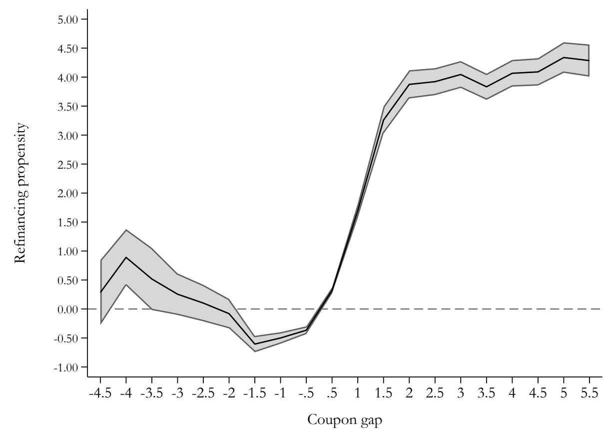
(a): No controls



(b): Controls



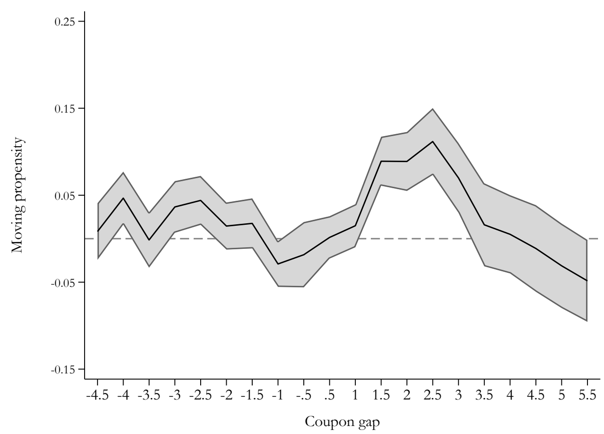
(c): Household Fixed Effects



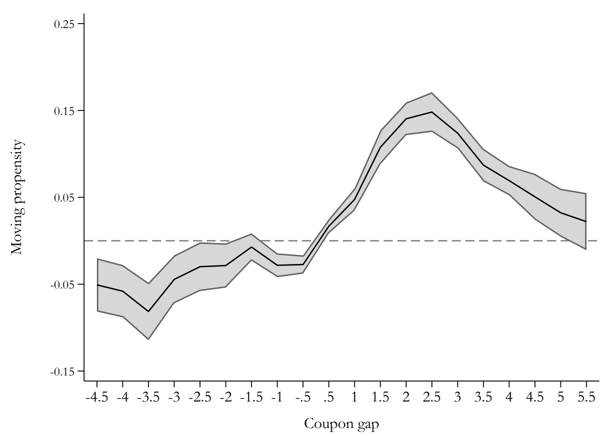
Note: **Panel A** shows the propensity to refinance as a function of coupon gap dummies with 50 bps intervals without controlling for further factors. **Panel B** shows refinancing propensities as a function of coupon gap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squared, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year-municipality fixed effects and remaining mortgage term fixed effects). **Panel C** shows the coefficient estimates controlling for household fixed effects. For interpretational purposes, the plots display the interval spanning the 0.5th to the 99.5th percentile of coupon gap values grouped into 50 bps bins, with the baseline coupon gap category set to zero across all panels. Standard errors are double clustered by issuance month-year and municipality.

Figure A-5: Moving propensities vs. coupon gaps

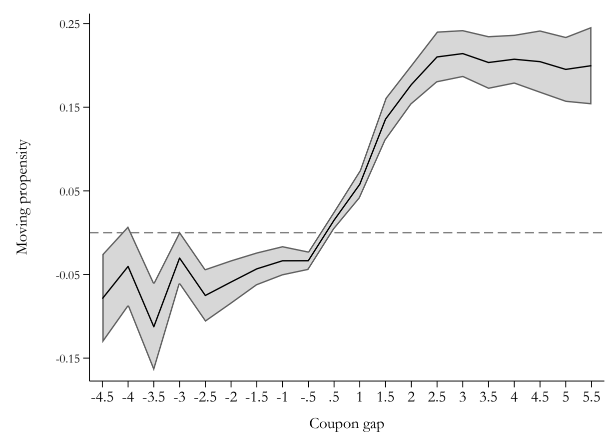
(a): No controls



(b): Controls

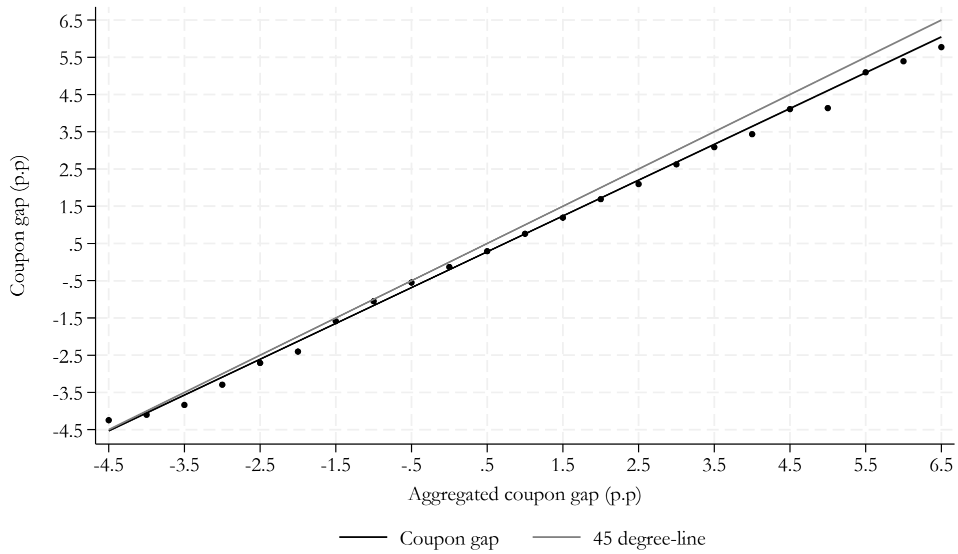


(c): Household Fixed Effects



Note: **Panel A** shows the propensity to move as a function of coupon gap dummies with 50 bps intervals without controlling for further factors. **Panel B** shows moving propensities as a function of coupon gap dummies at 50 bps intervals, while controlling for variables similar to Fonseca and Liu (2024) (household age, household age squared, gender (couple, single female, single male), log face value, log of average monthly mortgage payment, month fixed effects, year-municipality fixed effects and remaining mortgage term fixed effects). **Panel C** shows the coefficient estimates controlling for household fixed effects. For interpretational purposes, the plots display the interval spanning the 0.5th to the 99.5th percentile of coupon-gap values grouped into 50 bps bins, with the baseline coupon gap category set to zero across all panels. Standard errors are double clustered by issuance month-year and municipality.

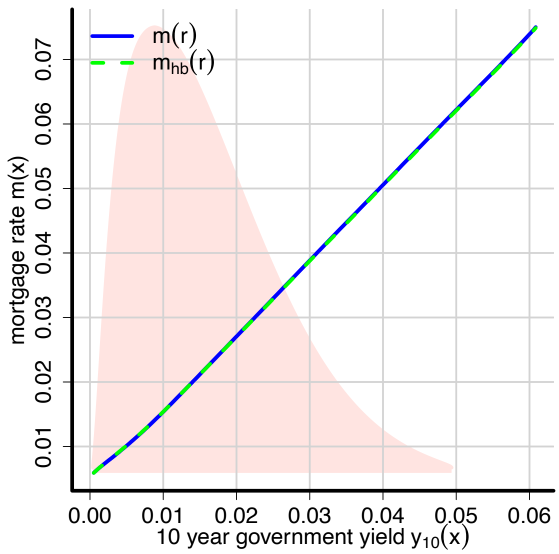
Figure A-6: Instrument relevance



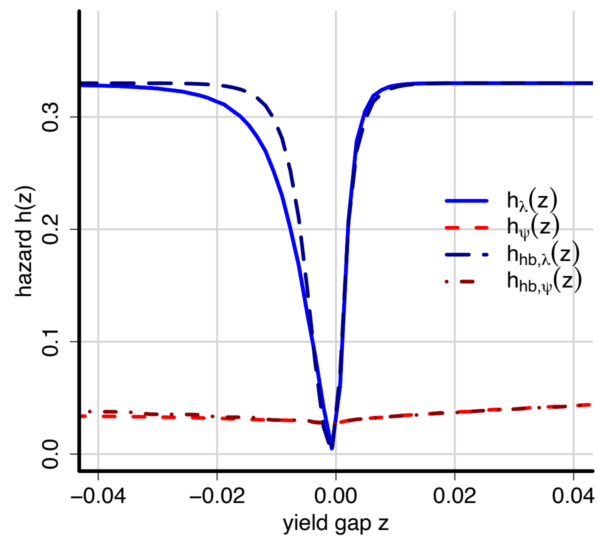
Note: The binscatter plots realized coupon gaps against the aggregate coupon-gap instrument, together with a fitted linear relationship and a 45-degree line.

Figure A-7: Different beliefs over rate persistence

(a): Mortgage rate $m(x)$



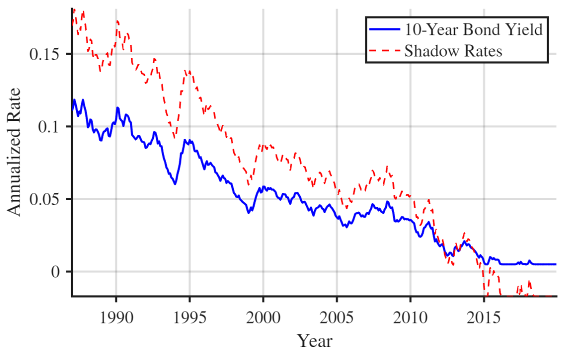
(b): Hazard rates $h(z)$



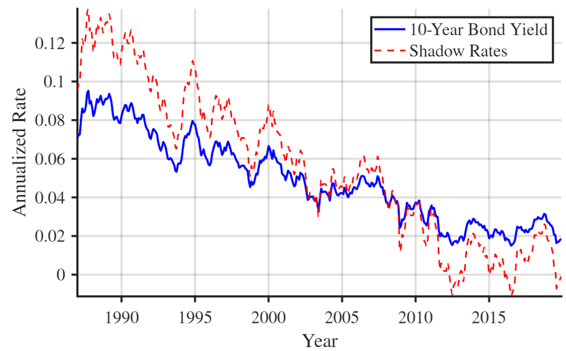
Note: Left figure shows the equilibrium mortgage rate $m(x)$ when households and the market have homogeneous beliefs (solid blue) and when households perceive the speed of mean reversion to be twice as fast as the market's belief (dash green). Right figure shows the implied refinancing, move and prepayment hazard rates, as a function of the yield gap z.

Figure A-8: 10-Year bond yield and estimated shadow rates

(a): Denmark



(b): U.S.



Note: The blue solid line plots the observed 10-year bond yield and the red dashed line shows the shadow rates over the period from January 1987 to December 2019. The shadow rates are estimated following the methodology described in Section IA.1.3.

Table A-1: Summary statistics for price dispersion

	Mean		Median		
Coupon (%)	SD	Spread	SD	Spread	N
0.5	0.26	0.57	0.23	0.51	50
1	0.35	0.74	0.32	0.72	58
1.5	0.29	0.62	0.26	0.54	98
2	0.41	0.89	0.39	0.87	98
2.5	0.44	0.92	0.37	0.79	103
3	0.49	1.06	0.41	0.87	83
3.5	0.38	0.82	0.36	0.77	78
4	0.35	0.70	0.28	0.60	147
5	0.46	0.98	0.28	0.62	199
5.5	5.07	7.17	5.30	7.50	3
6	0.32	0.69	0.24	0.50	134
6.5	1.92	2.72	1.77	2.50	4
7	0.35	0.77	0.28	0.61	74
All	0.40	0.84	0.31	0.65	1,129

Note: This table reports the monthly cross-sectional dispersion in issuer prices for fixed-rate mortgage bonds with 30–35 years to maturity. For each month, issuer prices are first averaged within each issuer and coupon bucket. The table reports the mean and median of the standard deviation of issuer prices ("SD") and the spread between the highest and lowest issuer prices across issuers ("Spread"). The "All" row pools all coupon buckets. N denotes the number of monthly observations.

Table A-2: Moving and the (piece-wise linear) coupon gap

	OLS			IV
	(1)	(2)	(3)	(4)
	Moving (pct)	Moving (pct)	Moving (pct)	Moving (pct)
Coupon gap (p.p.)	-0.0143***	0.0106**	0.00999	0.00400
	(0.00463)	(0.00453)	(0.00639)	(0.00445)
Positive coupon gap indicator	0.0398**	0.0330***	0.0258***	0.0780***
	(0.0152)	(0.00640)	(0.00821)	(0.0141)
Coupon gap X positive gap	0.0257***	0.0156***	0.0572***	0.0399***
	(0.00812)	(0.00460)	(0.00714)	(0.00573)
Controls		X	X	X
Household FE			X	
R-squared	0.0000113	0.000958	0.0411	0.000472
Root MSE	5.637	5.489	5.408	5.522
F-stat				217.8
Observations	66232863	63296890	63293856	60704869

Note: The table reports marginal effects on moving propensity of the coupon gap, an indicator for a positive coupon gap, and the interaction. For scaling purposes, the dependent variable is a binary indicator that takes the value 100 if the household moves. Column (1) reports estimates without additional controls. Column (2) adds a set of baseline controls following Fonseca and Liu (2024), including household age and age squared; household type (couple, single female, single male); log face value of the mortgage; log average monthly mortgage payment; remaining mortgage term fixed effects; month fixed effects; and year-by-municipality fixed effects. Column (3) adds household fixed effects to the regression of Column (2). Column (4) instruments the realized coupon gap using the difference between the market rate at the time of mortgage issuance and the market rate in the current month and year. Standard errors are double clustered at the issuance month–year and municipality levels and reported in parentheses, $^{*}\,p < 0.10$, $^{**}\,p < 0.05$, $^{***}\,p < 0.01$. The reported F-statistic is the Kleibergen–Paap rk Wald F-statistic, which tests instrument relevance in the presence of multiple endogenous regressors and cluster-robust standard errors.

Table A-3: Regime-switching shadow-rate model estimation

	Prior		Posterior		
Parameter	Mean	SD	Mean	SD	95% C.I.
η	0.170	0.050	0.1738	0.0116	[0.1554, 0.2003]
$\bar{x}$	0.030	0.020	0.0182	0.0043	[0.0083, 0.0261]
σ_{L}	0.008	0.008	0.0114	0.0006	[0.0105, 0.0128]
σ_{H}	0.025	0.020	0.0209	0.0009	[0.0201, 0.0233]
λ_{LH}	0.350	0.200	0.3260	0.1067	[0.0947, 0.4899]
λ_{HL}	1.000	0.500	0.8112	0.2123	[0.5146, 1.3635]
σ_y	0.0010	0.0015	0.00098	0.00003	[0.00095, 0.00108]
σ_v	0.800	0.100	1.0936	0.0438	[1.0035, 1.1743]

Note: This table reports posterior estimates from the regime-switching shadow-rate model of Section IA.1.4, estimated by particle marginal Metropolis–Hastings on monthly 10-year U.S. Treasury yields and TYVIX over 2003–2019. The volatility and rate parameters $(\bar{x}, \sigma_{\mathrm{L}}, \sigma_{\mathrm{H}}, \sigma_y)$ are reported in annualized decimal units and σ_v is in TYVIX (percentage-volatility) points. "95% C.I." is the 2.5–97.5 percentile credible interval of the post-burn-in draws.