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CHAPTER 9

Mortgage Prepayment Modeling: II

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INTRODUCTION

Over the last several years, the U.S. mortgage securities market has endured a dramatic range of prepayment experiences, frustratingly few of which were adequately predicted by existing prepayment models. Today, the market has both the motive and, for the first time, the opportunity to seek a superior approach to prepayment prediction.

Why mortgage investors need new prepayment models is clear: previous models have tended to provide seriously inaccurate predictions whenever the conditions influencing borrowers' prepayment decisions have changed to any significant degree. However, this very range of conditions provides the opportunity to substantially improve our quantitative understanding of prepayment behavior. We now have a wealth of data on the impact of changing interest rates and yield curve shapes, differences in loan size and transaction costs, varying housing market conditions, evolving regulations, and mortgage product innovation. Subtleties in seasoning patterns and the important distinctions among different vintages of mortgages have now become much clearer. Finally, the extended market rally that drove mortgage rates to successive lows provides the researcher with a perfect laboratory for examining refinancing behavior and, particularly, changes in the refinancing efficiency and composition of a mortgage pool over time.

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Goldman Sachs has taken advantage of this opportunity to develop an entirely new generation of prepayment models, based on data from the early 1970s to the present and spanning all the major fixed-rate, single family mortgage sectors—level-pay and balloon, agency and non-agency. This family of models, which we collectively designate the *new Goldman Sachs prepayment model,* is not an update of existing specifications, but represents a complete rethinking of how prepayment modeling should be done. Indeed, we believe it will establish a new market standard for prepayment research.

The new approach departs from previous models in many respects, two of which are particularly important: we model the individual homeowner's decision criteria more realistically and comprehensively than ever before, and we explicitly estimate the detailed composition of a mortgage pool in terms of its refinanceability. The focus throughout is directly on borrower behavior and decision-making, and we model these in a dynamic and path-dependent way that overcomes many of the problems that have plagued prepayment models in the past. The new model also provides three new measures of prepayment risk, along with substantially improved measures of duration and convexity, that offer significant insights into the valuation and hedging of prepayment-sensitive securities.

In thinking about mortgage prepayment models, investors should keep in mind three basic questions. First, what does it truly take to model prepayments realistically? Second, how well can a prepayment model—any prepayment model—actually work as the conditions affecting prepayment rates continue to change? And finally, what tangible benefits can more accurate prepayment modeling provide? In this chapter, we take up each of these three central questions in turn.

MODELING PREPAYMENTS REALISTICALLY—WHAT DOES IT TAKE?

In constructing our new prepayment model, we have used major advances in *data, estimation,* and *structure* to full advantage. In the pages that follow, we sketch the data and estimation aspects briefly and concentrate primarily on the structural properties of the new model.

Modeling prepayments realistically depends heavily on the availability of accurate and comprehensive data, including not just prepayment rates themselves but also the many variables that influence them. Both the quantity and quality of data relevant to prepayment modeling have grown enormously over the past few years, from both agency and non-agency sources. These now encompass a rich variety of mortgages and economic environments, to the point where today we have the ability to quantify a great many features of prepayment behavior.

Our new prepayment model distinguishes data by *mortgage characteristics* such as loan type, coupon, vintage, and dollar balance, as well as by *environmental variables* including interest rates and origination points for the entire term structure of mortgage alternatives (level pay, balloon, and adjustable rate), housing values, income tax rates, and relevant government regulations—every significant element affecting the prepayment decision. The abundance and diversity of data, built up over more than 20 years of MBS prepayment history, have enabled us to analyze the effects of each of these variables with a good degree of reliability; all of these are explicitly incorporated into the Goldman Sachs prepayment model.

Realistic modeling of prepayments also requires careful attention to a number of thorny statistical issues regarding the estimation of model coefficients. To guard against inconsistency and bias and to ensure the overall stability and robustness of the results, the modeler must properly address difficulties concerning the highly nonlinear relationships and interactions among the variables, the aggregation and relative weighting of various historical observations, the appropriate treatment of outliers, and the critical distinction between historical fit and predictive power.

At least as crucial as these data and estimation issues, however, is the conceptual structure of the analysis, which is what makes or breaks the ability of a statistical model to extrapolate past relationships into the future. We find that prepayment behavior reveals the greatest consistency over time when analyzed in terms of the true fundamental mechanisms and incentives underlying *homeowner decisions.* Once we "get inside the heads" of homeowners and their bankers, we can reflect these fundamentals as closely as possible in the mathematical structure of the prepayment model, to the full extent permitted by the data.

Despite all the revolutionary changes that have occurred in the mortgage market since the first MBS prepayment data of the early 1970s, and even though the prepayment behavior of U.S. homeowners is not theoretically "rational" by a long stretch, such behavior has been *extremely consistent* in key respects when viewed in terms of the real dollar incentives that homeowners actually consider in reaching their decisions. The consistent decision-making behavior of millions of homeowners, over long time periods spanning a wide range of circumstances, is what gives well-structured statistical prepayment models their potential for success.

Mortgage prepayment rates can be broken down into four primary structural components; accordingly, our prepayment model actually comprises separate "sub-models" of these four distinct mortgagor decisions:

Total Prepayments	=	(1) Relocations	−	(2) Assumptions	+	(3) Curtailments	+	(4) Refinancings

All four of these components need to be analyzed separately, using the appropriate set of variables and dynamics for each, for a prepayment model to perform realistically across the full range of possible securities and scenarios. When this is done properly, the result is greater consistency with historical prepayment behavior, less *ad hoc* curve-fitting, better out-of-sample performance, more reliable interpretation of prepayment trends as they occur, and a more robust framework for incorporating new developments as required. Indeed, we firmly believe that a prepayment model *needs* to work this way to have any hope of capturing the relevant complexities of actual prepayment patterns in a mature market.

Relocation

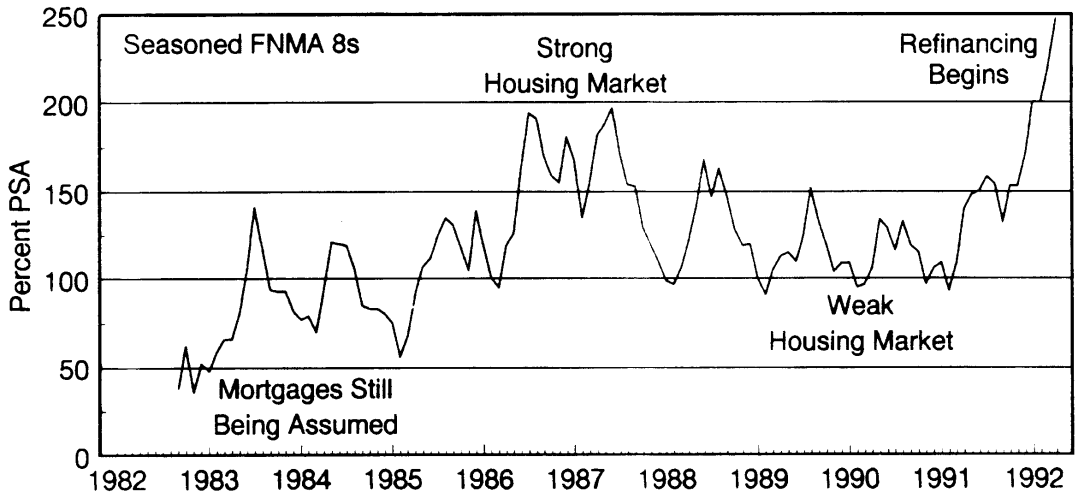
Relocation prepayments (whose definition we broaden slightly to include defaults, cash paydowns, and certain equity-takeout refinancings) are affected by a number of *economic considerations*, notably home equity levels, mortgage rates, and tax deductibility. Together, these influence the affordability of "trading up" to a larger home, and relocating homeowners tend to be very well informed about these variables. Relocations are also influenced by *noneconomic considerations*, such as the age of the loan, the yearly seasonal cycle, and the multiyear housing cycle. The new Goldman Sachs prepayment model distills the economic elements of the homeowner's relocation decision into a dollar measure of "relocation incentive," which then scales up or down the normal "demographic" or cyclical pace of relocations that would prevail in the absence of economic concerns.

Exhibit 1 shows 10 years of monthly prepayment rates on seasoned FNMA 8s (late 1970s originations), beginning with the issuance of the first pools in mid-1982. During most of this period, these 8s were discount mortgages, so their prepayment rates can reliably be taken as representing predominantly relocations.

In fact, during the early 1980s, relocation rates were substantially *faster* than the indicated prepayment rates, because in many cases the buyer of the home was able to assume the seller's conventional mortgage, and record market interest rates frequently made this an attractive option. However, the assumability of conventional mortgages was phased out as enforcement of the due-on-sale provision was standardized from 1982 to 1985. Since then, full repayment of any conventional mortgage has been legally required upon sale of the home. As a result, baseline prepayment rates for these securities today are substantially higher than what might be suggested by the early years of data.

As the subsequent prepayment history of the seasoned FNMA 8s shows, the pace of homeowner relocations is somewhat variable. During 1986–87, a period of strong housing activity and rising home prices, prepayment rates

Exhibit 1. The Relocation Baseline: Rate/Equity/Tax Incentives
(Plus Demographic Seasoning, Housing Cycle, Seasonal Cycle)

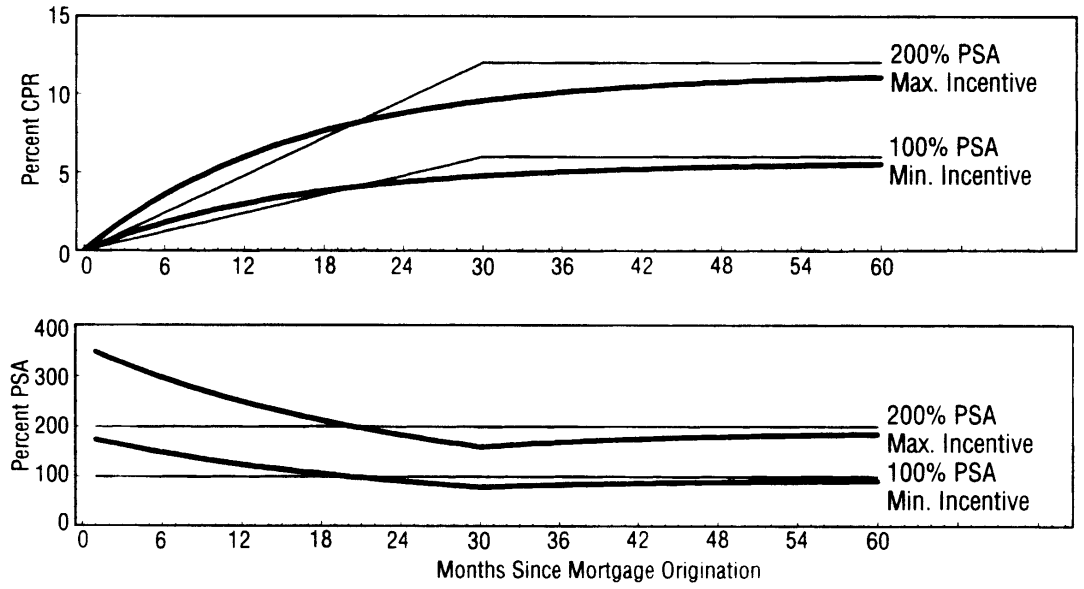


averaged more than 150% PSA. Around 1989–90, however, a severe downturn in the national housing market slowed relocation activity considerably, as reflected in average prepayment rates closer to 115% PSA. Seasonal patterns add a further degree of variability to short-term relocation rates, and different rates of home appreciation and equity buildup for different segments of the national housing market add some variability over the intermediate term.

But while these normal cyclical fluctuations will cause relocation prepayments to fall above and below long-term average rates for short periods, it seems clear that neither fast nor slow relocation rates are sustainable for more than brief episodes. (Interest-rate adjustments along the economic cycle tend to act as automatic stabilizers.) Certainly, 100% PSA is an excessively slow long-term prepayment scenario for most non-assumable 30-year mortgages; realistic projections for even deep discounts should generally be in the range of 120–150% PSA with normal buildup of homeowner equity.

It is worth recalling here how the standard PSA seasoning pattern, intended to approximate the increasing likelihood of relocation over time for 30-year current coupon mortgages, differs somewhat from the more realistic seasoning patterns actually observed for these and other mortgage types. Exhibit 2 is a schematic illustration of the relocation component of the Goldman Sachs prepayment model for 30-year conventional mortgages (with cyclical elements omitted for simplicity). In the top panel, the upper smooth curve represents our empirical estimate for the relocation rate, as a function of mortgage age, for a hypothetical mortgage pool with maximum economic

Exhibit 2. Relocation "Sub-Model" for 30-Year Conventionals



incentive (full equity and relatively low current mortgage rates). The lower smooth curve corresponds to a case of minimum economic incentive (negative equity and high current mortgage rates). On average, the smooth curves tend to outpace the simple PSA "ramp" profile in the early months after mortgage origination, and experience a relative shortfall concentrated at two to four years of age.

The lower panel of Exhibit 2 displays the same four seasoning profiles on the PSA scale rather than the CPR scale. It shows how demographic relocation patterns generally translate into a downward-trending sequence of PSAs through month 30, with a slight upward bias beyond that point (again, holding economic incentives constant). This effect is most pronounced for balloon mortgages, whose particular appeal to short-tenure homeowners results in a much higher rate of early relocations than called for by the PSA scale. In all cases, using the actual month-to-month sequence of prepayment rates projected by the Goldman Sachs model should result in more faithful timing of MBS cash flows than any single PSA speed.

Assumption

Upon sale of a home, under appropriate conditions, an existing FHA/VA mortgage may be assumed by the buyer rather than prepaid. Assuming the existing mortgage, though not a widely familiar procedure, in fact is often easier than qualifying for a new loan, entails minimal transaction costs, and

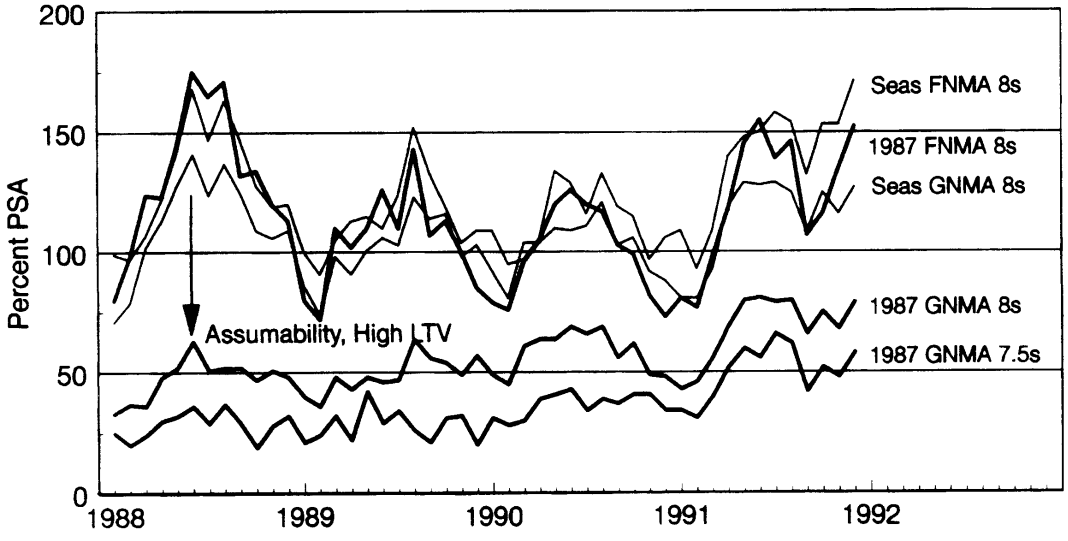
requires essentially no judgment on interest-rate timing. It appears to be the most rational prepayment decision of all, and in fact it is a very straightforward decision for a homebuyer to make.

When the interest rate of an assumable mortgage is low compared with current market rates *and* the LTV ratio is high enough to finance the buyer's purchase of the home (perhaps in combination with a small second mortgage at market rates), then the buyer's economic incentive to assume the mortgage can be compelling, and prepayment rates can fall substantially below the baseline relocation rate for sustained periods.

We can find extreme examples during the years of record high mortgage rates in the early 1980s. At one point, six-year-old GNMA 7.5s registered an astonishingly low 12-month speed of 8% PSA. A less extreme but more recent example is that of GNMA 7.5s and 8s originated at the bottom of the interest-rate cycle in 1987.

As Exhibit 3 shows, these 7.5s held below 40% PSA, and the 8s below 70% PSA, for four years after origination, a period when 9.5s and 10s were the current coupons. Analogously, we can now expect very slow speeds for recently originated GNMA 6s and 6.5s in today's market. Conventional discounts are no longer legal to assume, and seasoned, low-balance GNMA loans are no longer economic to assume (given today's home price levels), so the prepayment disparity between all of these and unseasoned GNMA discounts can be quite dramatic. Once again, quantifying the relevant dollar incentives at the homeowner level allows the Goldman Sachs prepayment model to track these patterns realistically and consistently across different mortgages and time periods.

Exhibit 3. Mortgage Assumability: Strong Effect on New, Large GNMA Loans

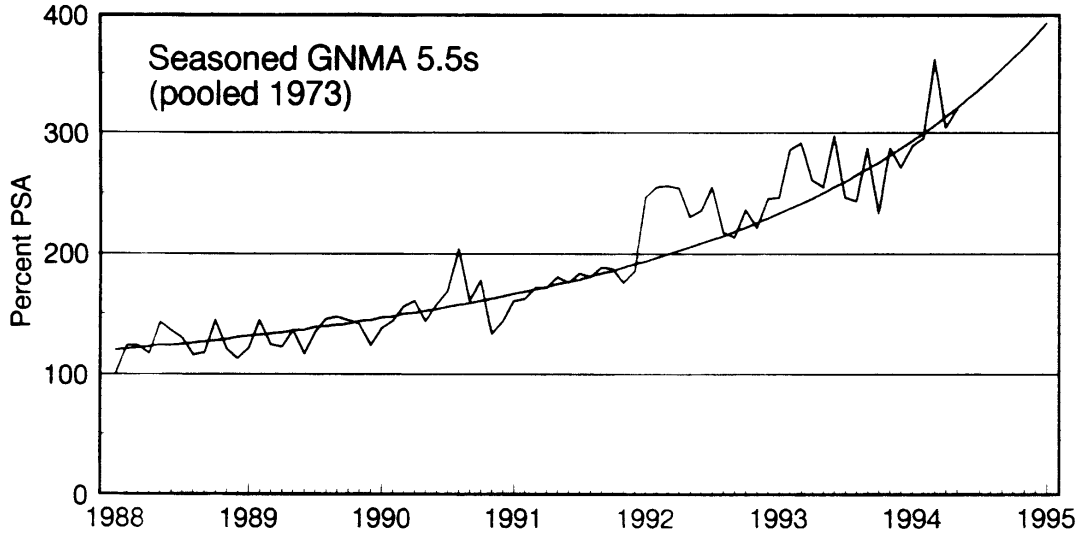


Curtailment

Although curtailments (partial prepayments of mortgages) generally account for less than 1% of total prepayment dollars at the beginning of the life of a mortgage pool, they can have a substantial *cumulative* impact on reported prepayment rates (and actual cash flows) as a mortgage pool seasons. An extra month's payment at the beginning of a 30-year mortgage can save a homeowner about an extra year of payments at the end, and the accelerated amortization in these future months is almost never fully captured by the weighted average maturity (WAM) of the pool. Instead, a portion of the accelerated amortization registers as "unscheduled" principal payments, raising the apparent prepayment rate of the pool. This effect is especially evident as the pool approaches maturity, when the scheduled principal amounts are large relative to the remaining mortgage balance. The effect is further exaggerated if the pool had a wide variety of mortgage maturity dates to begin with.

Exhibit 4 shows the consequences of curtailment for seasoned GNMA 5.5s, with an exponential acceleration pattern that recalls the old "FHA Experience" prepayment curves, and that clearly cannot be attributed to an acceleration in relocations or refinancings. The Goldman Sachs prepayment model captures the cash-flow effect of curtailment by projecting an appropriate increment to monthly prepayment rates to mimic mathematically the cash flows of a suitably accelerated pool amortization schedule.

Exhibit 4. Curtailment's Consequences: WAM Dispersion Effects



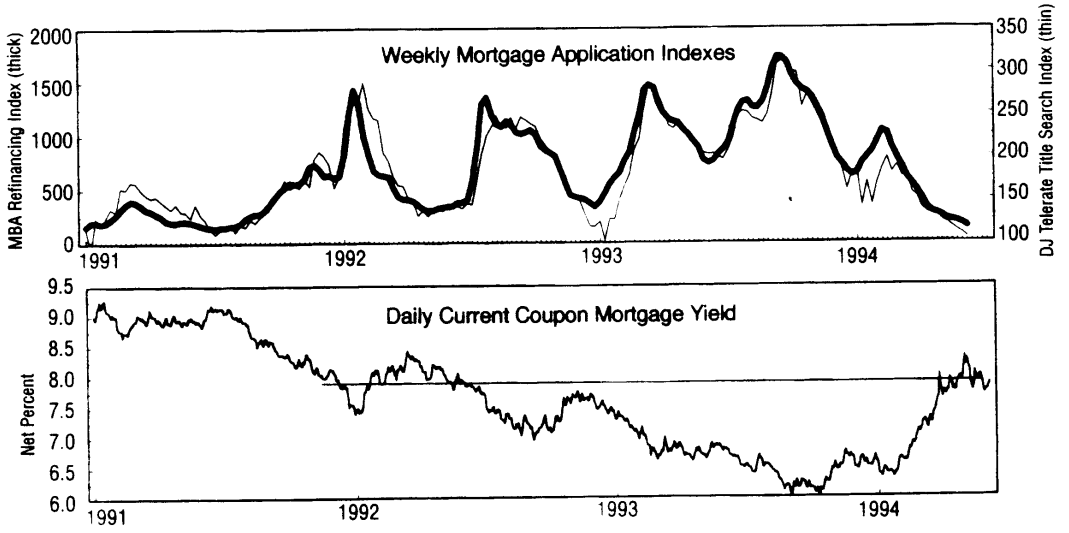
Refinancing

The most complicated type of prepayment from a modeling point of view, and the one that dominates valuation in most circumstances, is, of course, interest-rate-related refinancing. Fortunately, recent experience—the last three years in particular—has provided a treasure-trove of data with which to analyze refinancing patterns, and the new Goldman Sachs prepayment model makes great strides in sorting out their complexity. In a very real sense, we believe that for the first time ever, this volume of data now permits the estimation of a properly structured mortgage refinancing model.

Unlike the other three major components of mortgage prepayments, refinancing is greatly complicated by the property of *path dependency*. To forecast refinancing activity, it is not enough to know the current level of mortgage rates; we need to consider the whole historical path of mortgage rates that brought the homeowners to this point, to know whether they are experiencing a new level of refinancing incentive or just getting another look at an incentive level they already passed up in the past.

Once refinancing episodes have occurred, they can result in remnants of a mortgage pool with dramatically different prepayment behavior from that of the original pool before the episodes occurred. In particular, history teaches us that progressively lower lows in mortgage rates are usually required for reviving significant refinancing activity. As Exhibit 5 shows (using only 30-year fixed mortgage yields for simplicity), today's interest-rate levels are prompting virtually no mortgage refinancing activity (applications are

Exhibit 5. Path Dependency in Refinancing: Activity Surges Once Rates Set New Lows

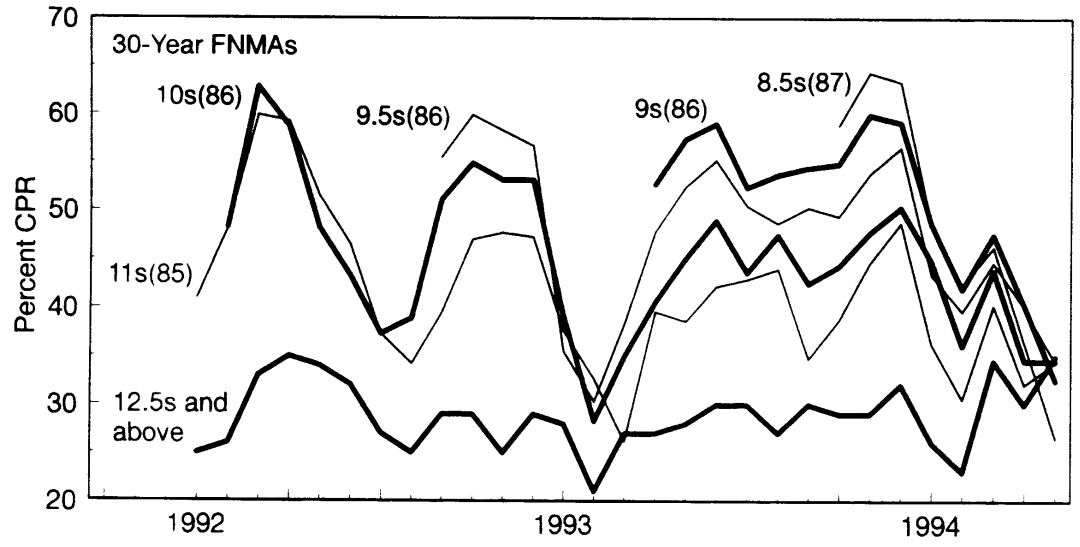


being filed at the slowest pace since 1990), whereas we experienced an unprecedented surge in refinancings when rates first declined to similar levels two years ago. This path-dependent behavior pattern has profound implications for valuing and hedging the prepayment option embedded in mortgage securities—and it so happens that the 1991–93 market rally, with mortgage rates notching down 50 bp to new lows every six months or so, provides a nearly perfect laboratory for analyzing this behavior in depth.

One of the most widely discussed refinancing patterns, the phenomenon referred to as "burnout," is also one of the most widely misunderstood—probably owing to overly casual use of the term. Burnout does *not* mean that refinancing speeds on a mortgage pool can be expected to decline continually over time; rather, speeds will generally exhibit sizable short-term fluctuations around a *gradual declining trend*, once a full-strength refinancing episode has begun.

Exhibit 6, showing monthly prepayment rates for a range of coupons that refinanced heavily during the two-year rally, illustrates the true nature of refinancing burnout. Note how, by late 1993, each coupon starting from 8.5% ended up faster than the next-higher coupon—a pattern that can be explained only by the more extensive prior refinancing of the higher premiums. Observe also that conventional 10s were the fastest-prepaying coupon when they first became fully refinanceable in early 1992, and that although they reaccelerated substantially each time mortgage rates dropped to new lows, each crest was lower than the last. On average, their speeds followed a declining trend of roughly 10% CPR per year—even with mortgage rates

Exhibit 6. Refinancing and Burnout Occur "Layer by Layer"



sinking at the rate of 100 bp per year—and monthly speeds declined much *more* abruptly each time mortgage rates firmed up and stopped setting new lows. Nevertheless, it is clear that each stage of the rally brought new "layers" of people into the refinancing process, and this is the behavior we need to focus on.

As we can see, even FNMA 11s experienced an acceleration in prepayments as the current coupon fell from 7% to 6% during 1993, demonstrating that some homeowners were actually willing to refinance for 500 bp of savings who weren't willing for 400 bp. There may not have been *many* such homeowners, but that tier of interest-rate sensitivity clearly exists within the premium mortgage sector. This relentless refinancing by new layers of homeowners every time rates set new lows—up through *very* high premiums—is what makes it so difficult for premium pass-throughs ever to rally very far, and is thus what keeps their effective durations down.

All these observations make sense in the context of the refinancing histories of various coupons, but until now it has been extremely difficult for a prepayment model to capture this behavior with any degree of realism. In fact, one of the *most* severe and widespread shortcomings of traditional prepayment models is the chronic underestimation of the interest-rate sensitivity of partially burned-out premium mortgages, and therefore the chronic overestimation of their option-adjusted spreads and durations.

To overcome these problems, we have to begin with the basics: the essence of refinancing burnout is *the change in composition of a mortgage pool over time* as the most rate-sensitive homeowners exit the pool. Therefore, the refinancing component of the Goldman Sachs prepayment model explicitly attempts to estimate these changes in pool composition. It does this across three different dimensions, modeling the refinanceability of a mortgage pool in terms of the fractions of homeowners who are "Ready, Willing, and Able" to refinance.

Homeowners are *Willing* to refinance if the financial incentive is high enough to meet their requirements. We use the measure of refinancing incentive actually considered by typical homeowners and their bankers: *not* an abstract interest-rate differential or *ad hoc* statistical artifact, but the real dollar savings expected on an after-tax basis, taking into account an appropriate mix of available mortgage rates and points. There is a *continuous spectrum of homeowners* in terms of incentive requirements, ranging from those willing to refinance for just marginal savings to those willing to refinance only at extremely high incentives. In a significant departure from previous modeling practice, we estimate and keep track of this entire distribution within each mortgage pool. Then, with each passing month, the levels of current mortgage rates and transaction costs determine what fraction of the homeowners in the distribution should be considered Willing to refinance that month.

Raise the refinancing incentive with a 100 bp rate decline, and another segment of the distribution becomes Willing. Lower the refinancing incentive with a 100 bp sell-off, and many Willing prospects become Unwilling.

Whether a homeowner is *Able* to refinance is a different question—possibly a question of credit situation (unemployment or over-indebtedness), of resources (shortage of cash, income, equity, or time), of moving soon (always a sizable fraction of U.S. homeowners), or sometimes just of temperament. These are all *non-interest-rate elements* in the refinancing decision. And for individual homeowners, this Able or Unable classification can change over time; so burned-out mortgage pools can and do "recharge" if they have the opportunity to season without refinancing for a period, gradually replenishing the supply of Able refinancers. We model this with a slow, continual flow of homeowners between the Able and Unable categories as their preferences and circumstances change and the mortgages season.

Finally, of those mortgagors who are Willing and Able to refinance, only a small fraction are actually *Ready* to prepay in any given month (no more than about an eighth of any sizable mortgage pool). This can be thought of as a question of *timing*: indecision over interest rates, procrastination, holidays, pipeline lags, and so forth. It is not necessarily a matter of homeowner sophistication; very often it just takes several months for individuals to respond to financial opportunities.

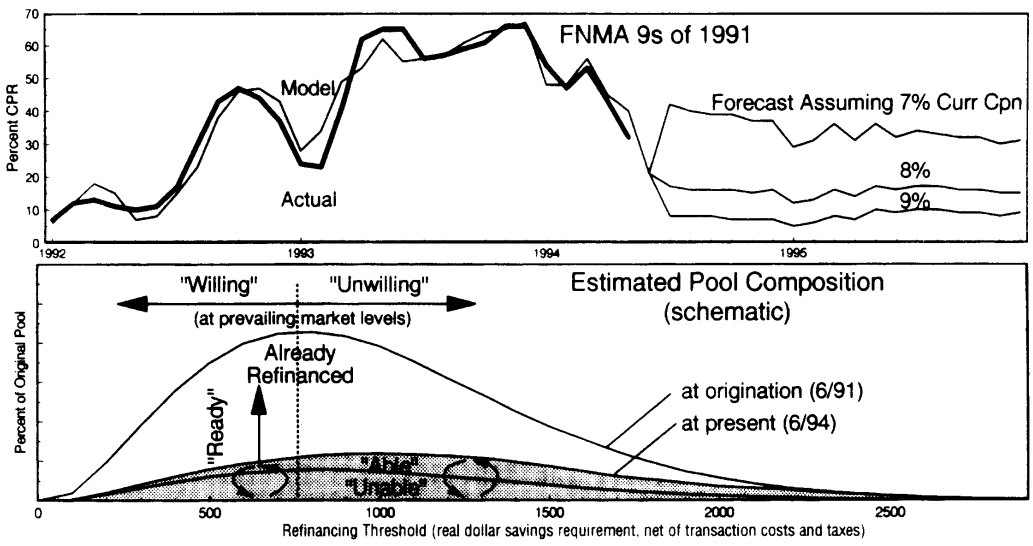
What our refinancing sub-model attempts to do is track the entire distribution of homeowners in a mortgage pool as it evolves over time, across all three dimensions of the Ready, Willing, and Able framework. This compositional analysis can be viewed as the MBS equivalent of "card counting" in blackjack: if you know what's in the deck when you start and you can keep track of what gets pulled out along the way, then you gain substantial insight into what's left as the deck winnows down—except that in the case of a mortgage refinancing model, we have to figure out first "what's in the original deck" and then "how to read the cards." Neither the initial distribution of homeowner refinancing characteristics nor the way that they evolve over time is directly measurable; they have to be inferred from empirical prepayment rates, quantified so as to be thoroughly consistent with the data. (Not surprisingly, this is the most challenging part of the statistical estimation.) Once this is done, however, highly realistic path-dependent spike-and-burnout prepayment patterns, option-adjusted spreads, and interest-rate sensitivities (durations and convexities) all emerge naturally from the way the various categories of Ready, Willing, and Able refinancers are depleted and replenished over time, over a wide range of market conditions.

This "compartmental" model structure is self-reinforcing: as incremental prepayment data for specific securities arrive each month, this increased information flows back into continually updating our estimates of the pre-

payment characteristics of the underlying mortgagors. Various market participants and academic researchers[1] have taken steps toward this methodology in the past, but generally with oversimplified model structures and insufficient data. We believe that the Goldman Sachs model is the first of its kind to actually succeed with the problem.

Exhibit 7 shows a simplified schematic representation of 1991 FNMA 9s as tracked by the refinancing sub-model. In the lower panel, the horizontal dimension represents the continuum of homeowner refinancing thresholds, and the vertical dimension indicates what percentage of the original pool we believe has a Willingness threshold in each range of dollar values. The outermost bell curve depicts the Willingness distribution of the pool at origination; the shaded area depicts what we consider to be the distribution of the pool today, now that successive waves of refinancing have chipped away large segments of the original composition of the pool. By now, we find that only a

Exhibit 7. The Refinancing Decision: Distribution of Homeowner Incentive Requirements



1 Dunn, K.B. and J. J. McConnell, 1981, Valuation of GNMA mortgage-backed securities, *Journal of Finance* 36, 599–617. Dunn, K.B. and C.S. Spatt, 1986, The effect of refinancing costs and market imperfections on the optimal call strategy and the pricing of debt contracts, Working paper, Carnegie-Mellon University. Johnston, E.T. and L.D. Van Drunen, 1988, Pricing mortgage pools with heterogeneous mortgagors: empirical evidence, Working paper, University of Utah. Richard, S.F. and R. Roll, 1989, Prepayments on fixed rate mortgage-backed securities, *Journal of Portfolio Management* 15, 73–82. Stanton, R., 1995, Rational prepayment and the valuation of mortgage-backed securities, *Review of Financial Studies* (forthcoming).

small fraction of the pool is left, retaining a disproportionate fraction of Unable refinancers, and with most of the remaining Able refinancers Willing to refinance only under conditions providing significantly higher incentive levels than today's.

In the upper panel, we show the actual prepayment implications of this analysis for the FNMA 9s. The left portion shows how the model has tracked the pool's considerable fluctuations in prepayment speeds over its two years of refinancing, and the right portion goes on to show the monthly prepayment speeds we would project for three different levels of interest rates. Note in particular that even a 100 bp rally should bring prepayment rates on these securities only about halfway back to their former peak, since so many of the more Willing and Able refinancers have left the pool over the last two years.

In fact, since the start of 1994, the premium mortgage market has gone from one extreme of interest-rate sensitivity to the other (extremely treacherous to surprisingly tame). In January 1994, a 50 bp rally would have brought us yet another new low in mortgage rates and sent the whole country racing to refinance yet again. In June 1994, a 50 bp rally would have merely returned premium mortgagors to refinancing incentives they had already been passing up for the previous two years. Thus, we strongly believe that prepayment speeds for the rest of 1994 will be much slower and more stable than for comparably priced premiums in 1992–93, and hence that the negative convexity of the mortgage sector has been greatly alleviated.

Exhibit 8 portrays some further interesting conclusions from this line of analysis. Coupons originated with a low percentage of *experienced refinancers* (such as 10s and above, virtually all of which were home purchase mortgages) start out with a high percentage of "inefficient" homeowners in the Willingness distribution—many who would be Willing to refinance for only marginal savings as well as many who would be Willing to refinance only for extremely high savings. Visually, the original distribution of FNMA 10% homeowners by refinancing threshold is thicker in both tails, compared with the original distribution of FNMA 9% homeowners.

Conversely, coupons originated with a high percentage of previous refinancers (such as 8s and below, either from 1987 or from 1992–93) appear to start out with a lower percentage of inefficient homeowners on both extremes and proportionally more homeowners who, from experience, "know when" to refinance most advantageously. We would conclude from this analysis that 1994 7.5s and 8s, which contain very few refi originations, should be substantially less efficient about refinancing in a future rally than the 7.5s and 8s of 1987 or 1992–93, which include a much heavier concentration of refi originations. This distinction could make for some interesting vintage effects in the market going forward.

In Exhibit 9, we see another significant example of pool composition effects, in this case a highly unusual comparison between the refinancing patterns of the 1985 and 1989 vintages of FNMA 11s. When this coupon became refinanceable in early 1991, the older vintage started out with the

Exhibit 8. Previous Refinancers Behave More "Efficiently"

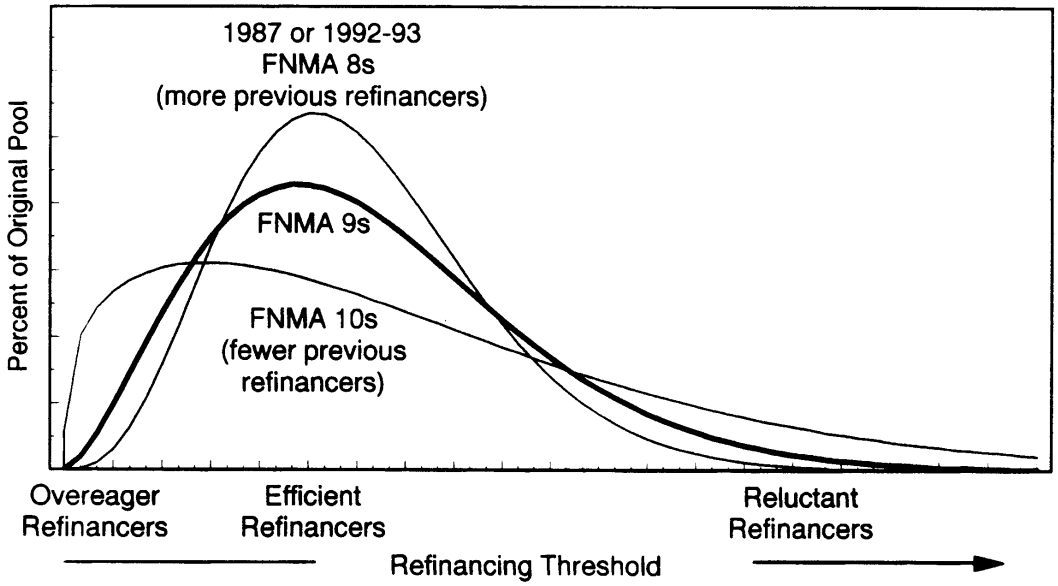
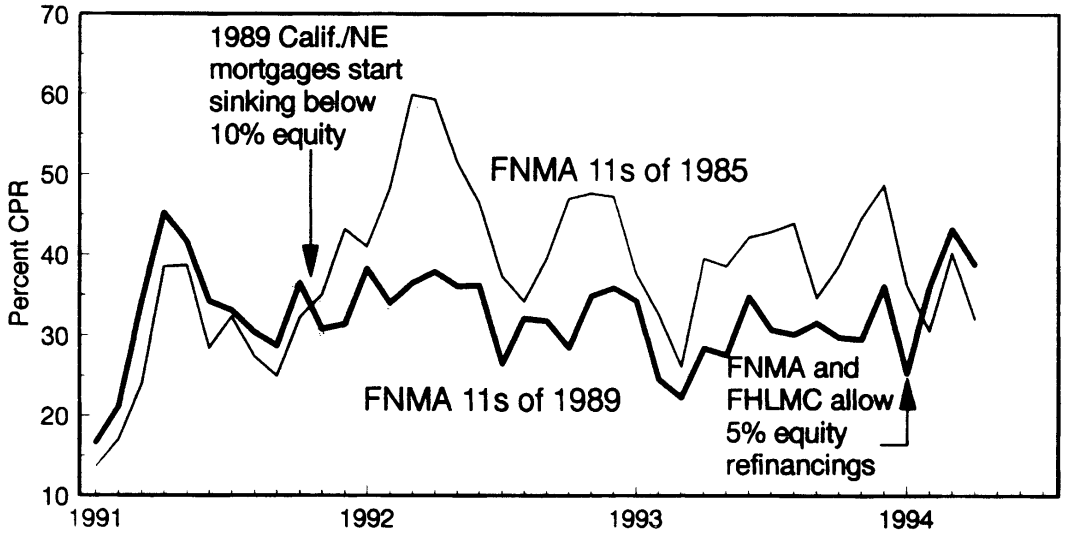


Exhibit 9. "Ability" to Refinance: A Critical Ingredient



slower speeds, as we would expect given its burnout from the 1986–87 refinancing wave, and given the smaller dollar refinancing incentives resulting from its smaller loan balances. However, by late 1991, the California and Northeast real estate downturns had gone far enough to drop many of the 1989 mortgages *below 10% equity* (the level that was required for refinancing at the time), and prepayment rates on the 1989 pools were greatly restrained relative to the 1985 pools. In our analysis, the 1989 mortgagors were every bit as Willing to refinance; they simply were not as Able.

This situation persisted for another two years, until in December 1993, both FNMA and FHLMC relaxed their underwriting guidelines to permit just 5% equity for refinancings. Suddenly the home appraisal *stopped* screening out such a large percentage of the 1989 refinancing applicants, with the result that these 1989 11s were among the very few mortgage issues to have prepaid *faster* in 1994 than in late 1993. Even with a nearly 200 bp backup in mortgage rates, prepayment rates for these 11s accelerated to three-year highs, once so many pent-up refinancings were released by making Unable refinancers Able again. The usual prepayment models, along with any price- or coupon-based rules of thumb for prepayment patterns, would miss out on such developments entirely.

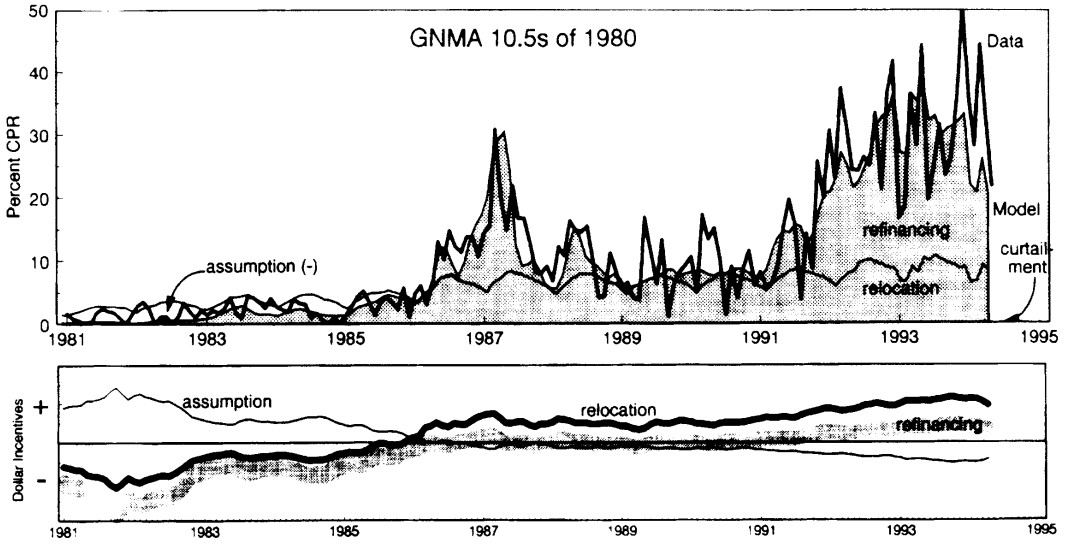
MODELING PREPAYMENTS REALISTICALLY—HOW WELL CAN IT WORK?

However plausible the methodology one chooses to pursue for modeling prepayments, at the end of the day the actual results are what matter. And since the mortgage agencies do not distinguish the four building blocks of prepayments in their reported data (much less the distribution of savings requirements of those who refinance), the entire Goldman Sachs prepayment model has to be estimated indirectly, through its consistency with historical aggregate prepayment rates. To gauge the success of such an undertaking, we propose three key properties of model performance to analyze: the tracking of prepayment *levels* (absolute prepayment rates), the tracking of prepayment *differences* (relative prepayment rates), and the tracking of prepayment *outliers* (aberrant prepayment rates). A model consistent with these three aspects of empirical prepayments is one that will have strong prospects for success in the marketplace.

Prepayment Levels

To illustrate, we start by examining (in Exhibit 10) the manner in which the four components of the Goldman Sachs model combine to track the prepayment history of a particular pass-through issue, 1980 GNMA 10.5%—not because this is an especially important coupon, but because it demonstrates

Exhibit 10. Tracking Prepayment Levels: Putting the Sub-Models Together



an unusual variety of historical prepayment experience. In the first years of its life, as mortgage rates soared, the dominant prepayment-related incentive was that of mortgage assumability. Refinancings were out of the question; even relocations were quite difficult to afford at the time with mortgage rates so high, and most relocations that did occur resulted in mortgage assumptions rather than prepayments.

These forces combined to produce the extremely slow prepayment rates of 1981–82. By 1985, easing mortgage rates and modest appreciation in home values had gradually eroded the assumability incentive, so even without a significant increase in housing turnover, the prepayment level began creeping higher. By 1986, these interest-rate and home-price trends had progressed far enough so that (1) the 10.5s were no longer economically assumable at all, and (2) relocation became an affordable option for the first time. Relocation prepayment rates appear to have jumped a notch higher, and at about the same time, the first refinancers in the pool swung into action.

Refinancing fluctuated around a borderline incentive level from mid-1987 through late 1991, and by 1992 a combination of lower mortgage rate levels (particularly those in the 15-year and adjustable-rate GNMA sectors) and lower transaction costs (from reductions in both origination points and FHA fees) had left virtually the entire pool with positive refinancing incentives, soon to surpass those experienced in 1987. Prepayment rates surged, and month-to-month variation became more pronounced as the outstanding number of loans in the issue, never large to begin with, continued to fall.

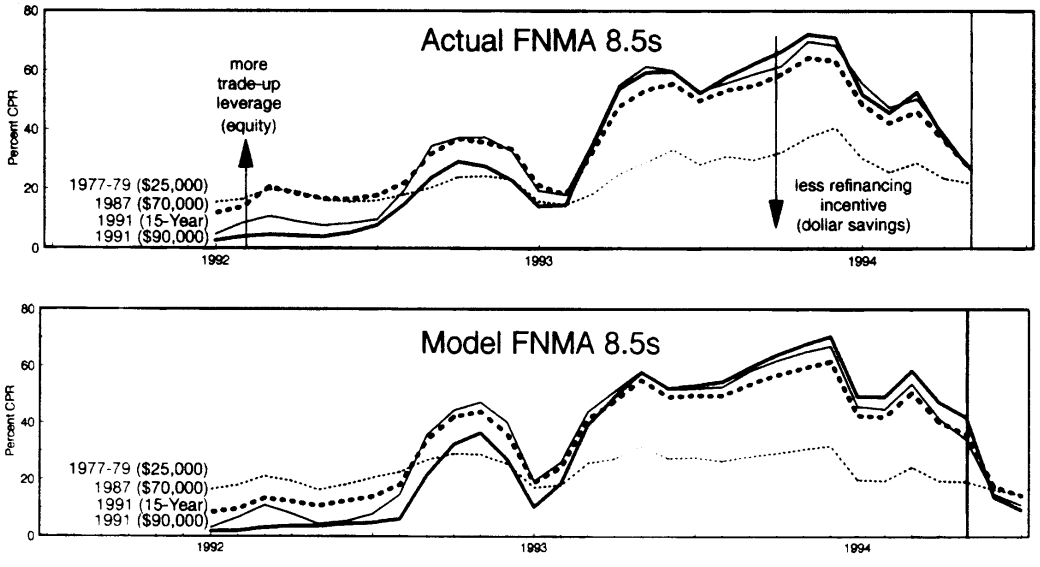
Likewise, the current slowdown, expected to continue in this coupon through at least the summer of 1994, is accompanied by a heavy dose of statistical noise. Curtailment is only now beginning to make a meaningful contribution to the prepayment mix.

The patterns traced by our four structural sub-models clearly do make intuitive sense for this coupon, and they track the total prepayment level consistently well (especially given the growing uncertainty inherent in a dwindling sample of loans). These are the kinds of verifications performed in developing and testing the Goldman Sachs prepayment model, not just "on average," but for the full range of individual issues—all relevant sectors, time periods, coupons, vintages, and loan sizes (including several tiers of jumbo whole loans). These validate the ability of a stable model of homeowner behavior to track the tremendous variation that exists in historical prepayment levels.

Prepayment Differences

Another, even more strenuous, test for a prepayment model is its ability to track relative prepayment rates, achieving suitably consistent results *across mortgage types, coupons, and vintages.* Exhibit 11 illustrates the ability of the Goldman Sachs model to reproduce the complex prepayment differences among four varieties of FNMA 8.5s (three major 30-year vintages and a 15-year counterpart). Here again, our approach of quantifying the fundamental homeowner incentives pays off.

Exhibit 11. Tracking Prepayment Differences



At the start of 1992, prepayments on these coupons were predominantly relocations, and the borrowers with the *smallest loan balances* (greatest home equity) had the most favorable economics for trading up to larger homes. The relative prepayment rates of the three 30-year issues reflected that relationship. Once the mortgages became high premiums for the first time, however, the *largest loan balances* provided the most favorable economics for refinancing, and so in 1993 the relative prepayment rates reversed their previous ordering. (This pattern extended to jumbo mortgages as well, where larger loan balances automatically resulted in even stronger refinancing incentives, faster premium prepayment speeds, and greater interest-rate sensitivity.) Because of these economic incentives, seasoned pass-throughs boast both superior extension protection (fast speeds as discounts) and superior call protection (slow speeds as premiums), significantly enhancing their stability, their convexity, and their value to investors.

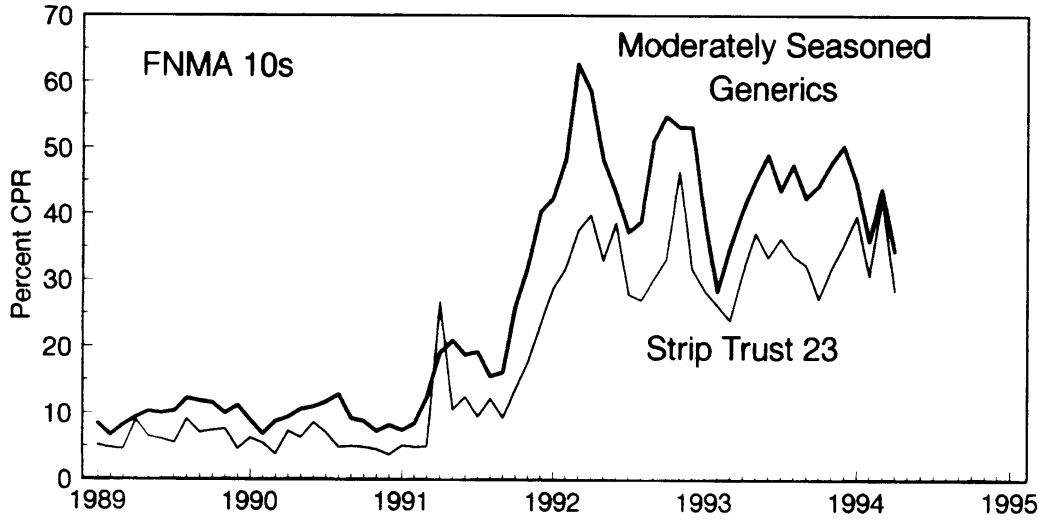
We believe the extent to which our new model captures the prepayment comparisons among securities such as these—and therefore the *value* comparisons among securities such as these—provides a level of realism an order of magnitude beyond previous models. In particular, quantifying homeowner prepayment incentives in real dollar terms is key to our understanding of many of these comparisons.

Prepayment Outliers

The third key aspect of model performance concerns the tracking of prepayment outliers. Once we venture beyond the market for generic "TBA" pass-throughs, some mortgage securities simply prepay consistently faster or slower than one would expect, given the fundamental characteristics reported for the pools. One example of this is FNMA Strip Trust 23, which for many years prepaid significantly more slowly than generic FNMA 10s with the same basic characteristics, whether as a discount or as a premium, as shown in Exhibit 12. The underlying influences behind such exceptional cases may never be fully discernible from the available data. Has a servicer been unusually inefficient? Has an originator catered to an unusually slow-prepaying segment of the population? Have the mortgagors been subject to a permanent local tax disincentive? Or have the prepayments instead been pent-up by a temporary equity shortfall, with the situation now starting to reverse? The truth in this case may well be a mixture of all these causes.

But even if we can't definitively identify the "reason" for the aberration, we should still take the aberration into account in analyzing the security (to the extent possible). We can do this by automatically testing the prepayment history of the specific set of mortgages in question (be they from a specific CMO, a certain pass-through coupon or vintage, or even a particular issuer

Exhibit 12. Tracking Prepayment Outliers



or geographic region) for systematic, *statistically significant deviations* from average prepayment behavior.

When, after we account for all the fundamental influences already built into the prepayment model, the deviations are large enough, consistent enough, persistent enough, and based on a large enough sample of loans, then we start to adjust our projections systematically with reference to those historical discrepancies. The more evidence there is that the specific mortgages are different from average, the more weight we give to their own history in choosing statistically appropriate forecasting coefficients for each separate component of the model—*not* the usual catchall "multipliers" that need to change every time interest rates move. The Goldman Sachs prepayment model's provisions for "custom alterations" are especially valuable for derivatives, but in fact they are useful for any mortgage security whose prepayment behavior consistently differs from normal patterns.

MODELING PREPAYMENTS REALISTICALLY—WHAT DOES IT GET YOU?

Improved prepayment modeling provides a much better qualitative understanding of general prepayment trends. It allows us to predict short-term prepayment movements with a high degree of accuracy and to anticipate reactions to significant changes in mortgage rates or other environmental influences. If we are sufficiently attuned to market expectations, this improved predictive accuracy can help us judge, in general terms, how the market will change security pricing in response to new releases of prepayment data.

Even more important, though, modeling provides us with a much better quantitative understanding of how prepayments affect specific securities. There are several major ways in which this shows up. Most obviously, models allow us to improve our *predictions of cash flows* in different market scenarios. This will always be the key to mortgage security valuation; without it, no other approach is likely to succeed.

Modeling also allows us to provide direct *relative value comparisons* across securities. By capturing the appropriate cash-flow distinctions among securities backed by mortgages of different type, coupon, vintage, loan size, refinancing efficiency, or prepayment history, we are able to provide richer and more reliable relative value comparisons across the MBS universe than we could otherwise obtain.

Also, with improved prepayment models, *hedging strategies* become more accurate and robust to different market conditions. Traditional mortgage models suffer from two serious problems with respect to their handling of risk. First, many models are unable to keep up with changes in market level, and the "model durations" they produce diverge substantially from the "empirical durations" with which the market trades the securities. Significant and persistent divergences of this type usually point to a fundamental misspecification of the interest-rate sensitivity of the prepayment model. Second, changing regulations and market innovations, such as periodic adjustments to the FHA insurance program and the advent of balloon mortgages, are difficult, if not impossible, to predict. Nonetheless, they can have substantial impacts on prepayment rates and security valuation. Until this time, it has been hard to quantify prepayment risk accurately. We now have three new and much better measures available to quantify prepayment risk, which we discuss in detail in a later section.

Finally, improved prepayment modeling allows us to approach a better fundamental valuation of mortgage securities. Prepayment risk is not necessarily diversifiable or hedgeable across all securities. But it is significant, and at times the market appears to demand incremental expected returns for securities that are significantly exposed to various aspects of undiversifiable prepayment risk. The standard measure of mortgage relative value, option-adjusted spread (OAS), does not account for the complete nature of prepayment risk. Rather, it adjusts for the optionality due to interest-rate fluctuations under the presumption that prepayment rates are a known, permanent function of interest rates.

As we improve our understanding of *intrinsic prepayment risk*, however, we can start to make better sense of OASs for securities with different prepayment risk profiles. For example, OASs for IOs have shown the ability to persist above 500 bp for extended time periods. In a real sense, we do expect that a high OAS is suggestive of high expected return (relative to an equivalent

position in Treasuries and options). But in the case of IOs, the reason for the high expected return may be that it is compensation for very significant prepayment risks that not even POs can fully hedge. Our new prepayment sensitivity measures allow a more precise quantification of those risks, thus enabling OASs to be viewed more meaningfully in the context of the prepayment risks that investors are taking.

Valuation Results

To indicate some of the model's functionality in tracking dynamic market changes, we show in Exhibit 13 two analytical snapshots of the conventional mortgage pass-through sector: first from June 15, 1994, and then compared with September 30, 1993, near the peak of the market. Being able to handle a change of the magnitude of this nine-month period, both in market level and in refinanceability, is a reasonably significant test.

The extension of *durations* in the mortgage market has by now been well publicized and understood. It shows up with equal drama in the model results: durations for 8.5s, for example, extended from 0.7 to 4.1 years. In September 1993, as the onset of new lows in rates resulted in extreme levels of interest-rate sensitivity, many market participants felt that premium pass-throughs were virtually unhedgeable and traded as cash. The model results confirm that empirical wisdom. As the durations extended, the long-term prepayment projections for 8.5s fell from 47% CPR to 9% CPR, while the 12-month prepayment projections declined even more dramatically, from 57% CPR to 7% CPR.

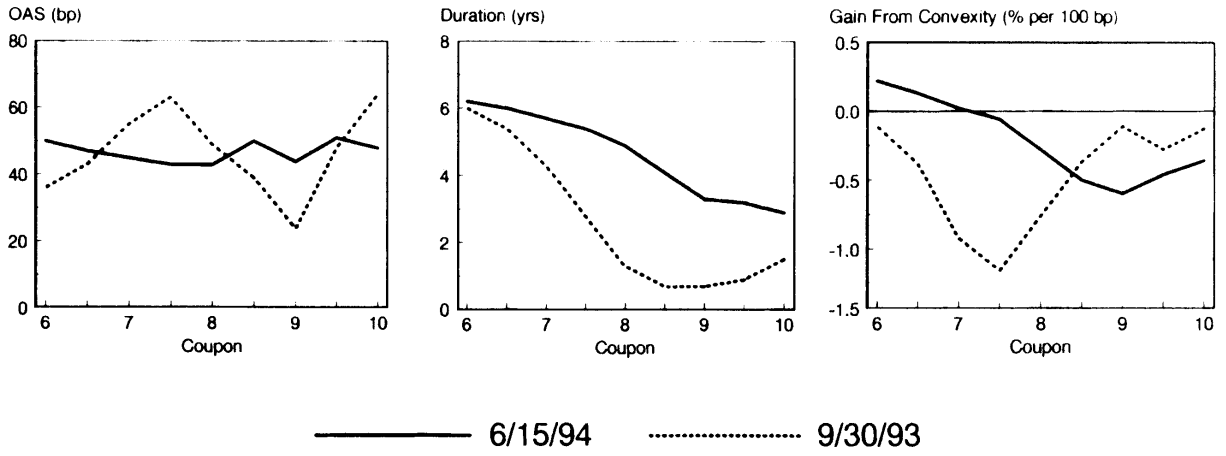
The move from extreme cuspiness to much more tameness in refinanceability can also be seen from the changes in *convexities*. The most negatively convex securities in September 1993 were 7.5s (experienced refinancers on the verge of their first repeat opportunity) with a convexity gain of -1.16% for a 100 bp market move. By June 1994, the worst convexity number was for 9s (a seasoned, heavily burned-out coupon) and was only -0.60%.

Finally, we note that the greater stability of CPR and duration estimates at June 1994 market levels was also mirrored in the greater consistency of pass-through pricing and *OASs*. The market of September 1993 experienced considerable pricing disarray coupon-to-coupon but, reassuringly, neither then nor in the middle of 1994 did our valuation model display any systematic bias toward higher or lower coupons.

All these changes between the two market snapshots seem reasonable given the magnitudes of the differences in mortgage rates and the makeup of the underlying pools, but capturing them is difficult for any model to do accurately. Now for the first time, with an appropriate framework for incorporating interest-rate sensitivity, our prepayment model goes a long way toward making OASs and durations the useful market indicators they were meant to be.

Exhibit 13. Conventional Pass-Through Valuation Summary

FNMA Coupon	6/15/94 Price	Static Yield	Static Spread	Avg Life	12mo CPR	LT CPR	LT PSA	OA Sprd	OA Dur	Gain Cnvx	Prepay Sensitivities Relo	Cusp	Refi
6.0	88-14	7.98	74	9.8	3	7	125	50	6.2	0.22	0.52	0.05	–0.01
6.5	91-18	7.96	72	9.8	3	7	131	47	6.0	0.13	0.41	–0.01	–0.02
7.0	94-18	7.96	74	9.6	3	7	140	45	5.7	0.02	0.31	–0.08	–0.03
7.5	97-10	8.00	78	9.6	3	7	144	43	5.4	–0.06	0.22	–0.12	–0.06
8.0	99-22	8.10	89	9.3	3	8	151	43	4.9	–0.28	0.15	–0.20	–0.09
8.5	101-28	8.17	101	8.2	7	9	159	50	4.1	–0.50	0.07	–0.31	–0.10
9.0	103-30	8.01	99	6.0	17	14	240	44	3.3	–0.60	–0.01	–0.37	–0.14
9.5	105-26	7.88	92	5.3	20	17	277	51	3.2	–0.46	–0.09	–0.33	–0.18
10.0	107-17	7.66	78	4.6	23	19	322	48	2.9	–0.36	–0.14	–0.33	–0.24



Prepayment Risk Measures

Despite the empirical fit of the Goldman Sachs prepayment model, investors may wish to analyze mortgage-backed security valuation using custom variations of the prepayment model, or they may wish to quantify the impact of an unanticipated change in the behavior of the underlying borrowers or their refinancing opportunities relative to our model. Although the salient features of prepayment behavior will remain the same—mortgage rate declines will always be associated with accelerations in prepayments—the magnitudes of the relationships can change. Recognizing that views may differ, and acknowledging the risks of relying on any single set of long-term assumptions, we have developed three economically independent measures of the price sensitivity of a security to key prepayment model parameters: the "relocation, cusp, and refinancing sensitivities." As with multifactor models of interest-rate risk, these prepayment risk measures can be used both as indicators of the relative sensitivity of a security to possible market changes and as hedging tools.

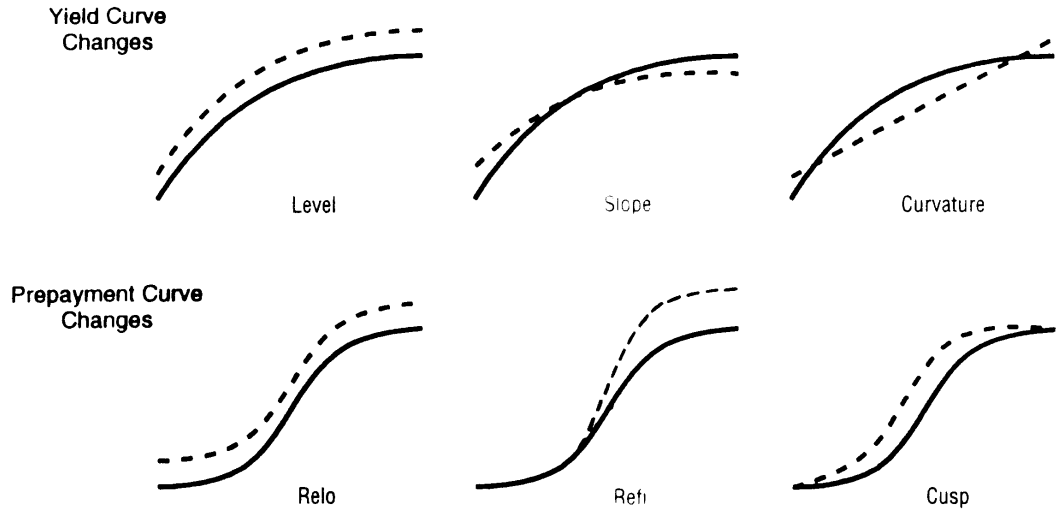
The *relocation sensitivity* measures the percentage impact on price of a 10% increase in the monthly relocation rates for each path of the OAS simulation. If an investor believes that relocation-driven prepayments in the future will be 10% faster than the model projects, the relocation sensitivity shows the percentage benefit in price if this view is true. Prepayment changes stemming from the underlying rate of economic activity or housing market patterns might show up here first.

Similarly, the *refinancing sensitivity* measures the percentage impact on price of a 10% increase in the monthly refinancings for each path. A future change in underwriting standards for refinancing, for example, could have an impact on the prepayment rates of high coupons and would best be hedged by using this variable. (Note that refinancing sensitivity will almost always be negative for mortgage pass-throughs—even those currently trading at discounts—since rate-related refinancing occurs only in scenarios where the pass-through is a premium and prepayments tend to reduce its value.)

The *cusp sensitivity* measures the impact of a shift of 25 bp in the prepayment function itself. This would capture the future impact of the introduction of a lower coupon mortgage program, such as balloons, or the impact of mortgage bankers lowering the cost of refinancing. Exhibit 14 sketches these three principal changes to the prepayment function.

In Exhibit 15, we show the output from our OAS model, including the prepayment sensitivities, for a selection of mortgage securities. The results for pass-throughs and strips are fairly straightforward. Refi and cusp sensitivities are magnified for the higher coupons (up to a point), and are significantly positive only for POs. Relo sensitivity is positive for POs and dis-

Exhibit 14. Quantitative Risk Measures



count pass-throughs, and negative for IOs and most premium pass-throughs. These results would probably accord with most investors' intuition, although the absolute levels may not.

The prepayment sensitivities can offer special insight into structured products, in particular. These measures can be used as an adjunct to traditional interest-rate risk measures to determine the true risk characteristics of a CMO class. The questions of "When is a PAC like a sequential?" or "When is a type II like a companion?" can be answered by comparing their prepayment sensitivity measures. As shown in Exhibit 15, the main difference among PACs, sequentials, and collateral at the moment is extension risk, and this is captured by their relocation sensitivities. Type II PACs, for example, generally have very high relocation sensitivities. Ranking these securities on the basis of OAS for relative value can then be weighed against their respective degrees of risk relative to the prepayment model.

Investors can also use these measures to hedge mortgages against changes in prepayment behavior. Hedging an IO—for example, with a Treasury using option-adjusted duration—will leave the position exposed to an unanticipated increase in the refinancing efficiency of borrowers, as occurred in 1993 for GNMAs as the result of a late-1992 FHA rule change. Investors can partly offset such risks by adding POs to the hedge, using the prepayment sensitivities to gauge how much of a particular PO strip to add. This leaves Treasuries hedging the interest-rate risk and POs hedging the prepayment risk.

Exhibit 15. Prepayment Risk Analysis (Pricing Date 6/15/94)

Security	Type	Collateral	OA Sprd	OA Dur	Prepay Sensitivities Relo	Cusp	Refi
FN 6.5	PT	—	47	6.0	0.41	–0.01	–0.02
FN 8.0	PT	—	43	4.9	0.15	–0.20	–0.09
FN 9.5	PT	—	51	3.2	–0.09	–0.33	–0.18
GN 6.5	PT	—	35	7.2	0.26	0.14	–0.01
GN 8.0	PT	—	37	5.9	0.08	–0.17	–0.10
GN 9.5	PT	—	52	3.5	–0.07	–0.44	–0.21
FN T249 IO	IO	FN 6.5	211	1.2	–2.95	–1.33	–0.13
FN T203 S2	IO	FN 8.0	446	–5.1	–2.95	–2.88	–0.49
FN T4 IO	IO	FN 9.5	698	–7.8	–3.35	–3.25	–1.29
FN T249 PO	PO	FN 6.5	–31	9.2	2.81	0.99	0.06
FN T203 S1	PO	FN 8.0	–166	10.7	2.23	1.55	0.20
FN T4 PO	PO	FN 9.5	–195	8.4	1.55	1.27	0.40
FN 9475 G	PAC I	FN 7.0	61	5.7	0.05	–0.09	–0.02
FH 1720 PG	PAC I	FH 7.5	68	5.7	0.06	–0.07	–0.01
FN 9475 M	PAC II	FN 7.0	38	5.7	1.74	0.27	–0.00
FH 1720 A	PAC II	FH 7.5	56	5.4	1.02	0.03	–0.02
FN 9479 A	Seq	FN 7.0	58	3.2	0.22	–0.03	–0.01
FN 9479 B	Seq	FN 7.0	40	6.4	0.55	–0.09	–0.02

CONCLUSION

A good prepayment model in a mature market has to be complex and comprehensive in looking at all aspects of homeowners' decisions. Because those decisions themselves are influenced by a considerable variety of circumstances, prepayment modeling must be detailed and sophisticated; it cannot be oversimplified if it is still to perform well. But it must also make solid, intuitive sense in the way it models the homeowner's decision dynamics. Anything less will result in a framework that is not sufficiently stable over time or sufficiently realistic over the "stress" scenarios that determine the value of mortgage securities. We have been guided by these two primary considerations of comprehensiveness and plausibility in developing the new Goldman Sachs prepayment model, and we believe the valuation and risk management results are likely to be significantly more accurate and robust than any previously available.