The decline in idiosyncratic values of US Treasury securities

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A B S T R A C T

Unique features and market frictions can lead to idiosyncratic pricing for some US Treasury securities. This study uses a linear programming (LP) model to measure aggregate idiosyncratic pricing of T-notes and T-bonds from 1980 to 2016. We document an average idiosyncratic pricing of $0.11 per $100 par, as compared to an average bid-ask spread of $0.08. Further, idiosyncratic pricing declined dramatically from the early 1980s to the 2010s. Empirical evidence suggests that the 1986 Tax Reform Act, increasing issue sizes and improving market liquidity contribute to the decline. At the individual security level, we identify factors contributing to and mitigating idiosyncratic pricing.

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Introduction

The Law of One Price states that securities or portfolios of securities with the same future cash flows should have the same prices. An important assumption is that securities are homogenous and perfect substitutes for each other. In other words, securities do not have unique features that might make them more (less) desirable for some investors and sell at higher (lower) prices than other securities or portfolios with the same future cash flows.1 In practice, market frictions and unique features may lead to higher prices or idiosyncratic values on some financial securities.2

This study uses a linear programming (LP) model to quantify aggregate idiosyncratic value in the marketable Treasury note and bond market and to examine its trend over the last four decades. The LP model assumes a perfect and homogenous Trea-

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1 Unique feature refers to specific bond characteristics that may make the bond more or less appealing to investors. For example, market discount bonds received preferential tax treatment before the 1986 Tax Reform Act.

2 Idiosyncratic value or pricing is defined as the price difference between one security and another security or a portfolio of securities with the same future cash flows. For example, many studies document higher prices for on-the-run Treasuries relative to otherwise similar off-the-run Treasuries and attribute the on-the-run effect to liquidity differences and/or repo specialness (Warga, 1992, Duffie, 1996). Furthermore, impediments to arbitrage can prevent potential arbitrageurs from exploiting idiosyncratic values (Hu, Pan, and Wang, 2013).

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The majority of idiosyncratic pricing is driven by inherent and persistent factors that are hard to arbitrage away.

More importantly, the LP solution shows a dramatic decline in the aggregate idiosyncratic pricing from the 1980s to more recent years, suggesting a significant reduction in unique features of individual Treasury securities and an increase in homogeneity in marketable US Treasury securities over the last four decades. The average month-end idiosyncratic pricing per security was $0.25 per $100 par value for the 1980 to 1984 subsample period. In contrast, the average per-security idiosyncratic pricing has decreased to less than $0.05 per $100 par value since 2010, a reduction of 80% in idiosyncratic pricing. Thus, the US Treasury market has been moving increasingly closer to the perfect and homogenous market as assumed by the LP model. This dramatic change coincides with several institutional and market developments and tax changes that tend to reduce market frictions, increase market homogeneity, and lower costs to arbitrage. Our empirical evidence suggests that the 1986 Tax Reform Act, increasingly larger issue sizes of Treasury securities, and improved market liquidity contribute significantly to the secular decline in idiosyncratic pricing.

At the individual security level, idiosyncratic pricing is concentrated in less than 30% of the securities. Furthermore, a relative valuation transition matrix allows us to track the month-to-month shifts between High-Priced, Fair-Priced, and Low-Priced securities, with Fair-Priced defined as having zero or minimal idiosyncratic pricing. We find that 86% of Fair-Priced securities remain Fair-Priced in the next month. Over 50% of securities heavily bought (Low-Priced) or heavily shorted (High-Priced) by the LP model remain heavily bought or shorted in the following month, strong evidence of persistent idiosyncratic factors.

Multi-logit models of relative valuation of individual securities shed more light on factors contributing/mitigating idiosyncratic pricing. For example, Fair-Priced securities have a larger percentage held in the form of Treasury strips, suggesting that the monitoring of relative prices of securities and stripping and reconstituting activities by bond dealers tend to reduce idiosyncratic pricing. More interestingly, our evidence shows that the on-the-run effect is more nuanced than documented in prior research. While on-the-run securities account for a disproportionately high share of High-Priced securities, the majority of them are Fair-Priced.

A recent study by Hu et al. (2013) develops an innovative market liquidity measure for the US Treasury market, which they call ‘Noise’ (HPW Noise hereafter). The HPW Noise effectively represents the average deviations of actual Treasury security yields from model-fitted yields. Hu et al. (2013) demonstrate that the measure is a good proxy for market liquidity and captures several liquidity crises.

While the HPW Noise is proposed as a measure of market liquidity, it can also be interpreted as a measure of aggregate idiosyncratic pricing of US Treasury securities. If the model-fitted yields are taken as the accurate underlying yields, then deviations of the actual yields from the model-fitted yields reflect the idiosyncratic value that investors are willing to pay (or demand) for special features. In that sense, HPW Noise is similar to LP Idiosyncratic Pricing. Indeed, the HPW Noise and the LP Idiosyncratic Pricing have a statistically significant correlation coefficient of 0.53 from 1987 to 2016.4 In addition, both HPW Noise and LP Idiosyncratic Pricing show large increases during the financial crisis of 2008–2009. However, the HPW Noise measure exhibits only a modest decline from 1987 to 2011 in contrast to the sharp decline for the LP measure. The differences are not surprising because of the different methods for computing each measure. Section 1.2 below and Appendix B provide a more detailed comparison of the two.

This study makes several contributions to the literature on idiosyncratic pricing and limitations to arbitrage. First, we propose an alternative non-parametric measure of aggregate idiosyncratic pricing that proxies for the magnitude of potential and theoretical arbitrage profits exploitable in frictionless markets without limitations to arbitrage. Second, we document a secular decline in idiosyncratic pricing, in the aggregate and per security, from the 1980s, suggesting reduced impediments to arbitrage or lower costs of arbitrage. The Treasury market has been moving increasingly closer to the perfect and homogenous market as assumed by the LP model. No prior study has documented the significant improvement in pricing efficiency.5 Third, our paper shows that liquidity, while important, is not the sole driver of idiosyncratic pricing; other factors, such as differential tax treatment and Treasury stripping activity, also affect idiosyncratic pricing.

The remainder of the paper is organized as follows. Section 1 introduces the linear programming model and compares the LP Idiosyncratic Pricing to the HPW Noise measure. Section 2 presents and discusses the empirical analysis of idiosyncratic pricing of US Treasuries. Section 3 investigates and analyzes the long-term trends in idiosyncratic pricing at the macro level and Section 4 examines idiosyncratic pricing at the individual Treasury security level. Section 5 concludes the paper.

1. The linear programming model and sample

Our premise is that limits to arbitrage and unique features of individual Treasury securities create differences between observed prices and theoretical prices, differences that would not exist in a frictionless and homogenous market. The unique features include tax effects, on-the-run effects, liquidity differences, short selling restrictions, collateral requirements, and others. Appendix C contains a summary of the literature about limits to arbitrage and unique features of individual Treasury securities.

We use linear programming to measure the aggregate value of the theoretical arbitrage profit in frictionless markets. The results show that these theoretical differences decreased markedly over time indicating that market frictions in the US Treasury bond market have decreased dramatically in the last four decades.

1.1. Linear programming model

The LP model assumes a tax-free arbitrageur operating in a frictionless and homogenous Treasury market with no limit or costs to arbitrage. Specifically, it assumes the following:

1. Transactions take place at the bid and ask prices.
2. No other trading costs (i.e., no brokerage commission and no price impact).
3. Securities can be short sold, and the proceeds be used without any restriction (i.e., no collateral or margin requirements for short positions).
4. There are sufficient supplies of securities to be short sold.6 A short sale can be for the full value of the securities without any so-called haircut (or discount).
5. There are no defaults on any payment or delivery obligations.
6. The tax rate on the arbitrageur is zero.
7. Positive net cash flows at a future point in time can be rolled over into subsequent points in time at a zero rollover rate (or forward rate).7

4 We thank Dr. Pan for making the Noise data publicly available.

5 While Hu et al. (2013) has similar sample period (1987 to 2011), its Noise measure is fairly stable other than spikes during several liquidity crises.

6 This assumption basically rules out the possibility of some Treasury securities trading on special in the repo market.

7 Since the horizons of these arbitrage solutions are very long, up to 30 years, we do not assume a reinvestment rate if the cumulative cash flow at a future point in
The above assumptions basically rule out any market frictions and impediments to arbitrage (e.g., brokerage commission, differential tax treatment, liquidity difference, etc.). However, the LP model explicitly incorporates bid-ask spreads. Thus, the idiosyncratic pricing from the LP model is net of the effect of bid-ask spreads.

The LP model has the following objective function

$$\max \{ I \} = \sum_{j=1}^{H} (X_j^a P_j^a) - \sum_{j=1}^{H} (X_j^b P_j^b)$$

(1)

where $P_j^a$ ($P_j^b$) is the bid (ask) price of bond $j$, $X_j^a$ ($X_j^b$) is bond $j$’s Short Weight (Long Weight), or the unit of bond $j$ to be shorted (bought), and $H$ is the total number of Treasury securities in the feasible set today, or time 0.

The maximization function in (1) is subject to the following constraints:

$$C_i = \sum_{j=1}^{H} (X_j^i c_j^i) - \sum_{j=1}^{H} (X_j^i c_j^i) \geq 0$$

(2)

and for $t > 1$,

$$C_t = C_{t-1} + \sum_{j=1}^{H} (X_j^t c_j^t) - \sum_{j=1}^{H} (X_j^t c_j^t) \geq 0$$

(3)

where $C_t$ is the net cumulative cash flows at time $t$, $c_j^t$ is the coupon or principal payment of bond $j$ at time $t$, and $t = 2 \ldots T$, and

$$0 \leq X_j^t \leq 1$$

(4)

$$0 \leq X_j^i \leq 1$$

(5)

The objective function in (1) tries to find a combination of long and short positions of bonds to maximize the cash flow at time zero, with the constraint that the cumulative net cash flows at each subsequent period from this long-short portfolio are never negative. The lowest value of the objective function is zero, which would indicate no arbitrage profit.\(^8\)

Since all T-notes and T-bonds in our sample make coupon payments and mature at either the end of the month or the 15th of the month, the payment period is defined as semi-monthly. Given the longest maturity of 30 years, the maximum $t$ in inequality (3) is 720 ($30 \times 12 \times 2$).

Inequalities (4) and (5) require that an arbitrageur can buy or short no more than 1 unit of each security to make sure the arbitrage profit is bounded. Thus, the total number of constraints of the LP model is 720+ (2 x the number of Treasuries).

The symbol $I$ in the objective function (1) is the theoretical arbitrage profit that can be achieved by a tax-free arbitrageur under a perfect and homogenous market. In a frictionless market without any security-specific unique features, competition among arbitrageurs should reduce the theoretical arbitrage profit to zero. Thus, the LP solution represents the aggregate idiosyncratic pricing due to unique features of some Treasury securities and limits or costs to arbitrage.

Appendix A uses a hypothetical example of six Treasury securities to illustrate the LP methodology. LP approaches have been used in bond portfolio optimization (Hodges and Schaefer, 1977) and in studies of the tax-specific term structure (Schaefer, 1981, 1982; Ronn, 1987).

1.2. Comparison with HPW noise measure

As mentioned earlier, Hu et al. (2013) develop a measure of overall market liquidity, called Noise. The HPW Noise is constructed in a two-step procedure. First, the Nielson-Siegel-Svensson model is utilized to fit daily zero-coupon yield curves by minimizing the weighted sum of the squared deviations of the actual bond prices from the model-fitted prices. Next, deviations of the actual bond yields to maturity from the model-fitted yields are calculated. The Noise measure is then defined as the root mean squared yield deviations. Hu et al. (2013) demonstrate that the measure is a good proxy for market liquidity and captures several liquidity crises.

The HPW Noise is essentially an aggregate measure of deviations of bond yields from model-fitted yields. If the model-fitted yields are taken as the accurate underlying yields, the HPW Noise can also be interpreted as a measure of aggregate idiosyncratic pricing of US Treasury securities in that the yield deviations reflect the idiosyncratic pricing that investors are willing to pay (or demand) for special features. In that sense, the HPW Noise is similar to the LP Idiosyncratic Pricing.\(^9\)

Though similar, the two approaches are different in several ways. To compare and contrast the two approaches, we construct a hypothetical numerical example and calculate the two measures of idiosyncratic pricing for six different scenarios. The details of the numerical example and the findings are contained in Appendix B. The following is a summary of the differences and similarities of the two measures as shown in detail in Appendix B.

1) Both approaches work well in identifying idiosyncratic pricing in their respective scales. HPW Noise measures idiosyncratic pricing in yield deviations while LP model measures idiosyncratic pricing in dollar terms. The difference is that the LP approach captures the price impact of yield differences for individual maturities. Although there are differences in the approaches, the two measures are positively correlated, consistent with our empirical finding of a significant correlation for a subsample of month-end data from 1987 to 2016.

2) The HPW Noise measure is a noisy measure of idiosyncratic pricing. It can be positive in the absence of any idiosyncratic pricing. More importantly, HPW Noise can be affected by factors other than idiosyncratic pricing, such as the changes in the shape of the yield curve. In contrast, the LP approach does not require any model to estimate the zero-coupon yield curve from the observed prices of coupon-bearing bonds, making the LP empirical results independent of specific models and free of potential model misspecifications. As a result, the LP model does not produce false positive idiosyncratic pricing in its absence.

2. Empirical analysis

At the end of each month from 1980 through 2016, the LP model uses daily quoted bid and ask prices, adjusted for accrued interest, to find the maximum theoretical arbitrage profit, or $I$ in the objective function (1), which will be referred to as Total Month-end Idiosyncratic Pricing in the remainder of the paper. The bid and ask prices are based on a $100 par value. As argued earlier, the Total Month-end Idiosyncratic Pricing measures the aggregate Treasury market idiosyncratic pricing due to unique features/market frictions and limits or costs to arbitrage.

\(^{8}\) Fontaine and Nolin (2017) also present a non-parametric measure of idiosyncratic pricing in the Treasury market and compare the trading profits from their strategy with the HPW Noise measure.
Table 1
Descriptive statistics of the US Treasury securities.
This Table reports the descriptive statistics of the US Treasuries in the sample. We include all non-callable, non-flower, fixed coupon and fixed principal US T-notes and T-bonds. Coupon Rate is the fixed coupon rate in percent. Issue Size is the original amount of issuance, in million dollars. Maturity is the years to maturity at issuance. Panel A reports the descriptive statistics for the whole sample from 1980 to 2016. Panels B and C report descriptive statistics for the 1980–1997 and 1998–2016 subsample periods respectively. The sum of the numbers of Treasuries in panels B and C is larger than the number of Treasuries in panel A due to some US Treasuries spanning the two subsample periods.

| Panel A: Whole sample from 1980–2014 | No. of Treasuries | Mean | Median | Std. Dev. | Min. | 10th Percentile | 90th Percentile | Max. |
|-------------------------------------|-------------------|------|--------|-----------|------|----------------|-----------------|------|
| Coupon Rate (%)                     | 1422              | 5.472 | 5.125  | 3.773     | 0.125| 0.875          | 10.750          | 16.250 |
| Issue Size (million $)              | 1422              | 18,656.988 | 16,086.500 | 11,235.820 | 627.000| 4608.000      | 35,000.000     | 45,489.000 |
| Maturity (years)                    | 1422              | 6.029 | 5.000  | 6.475     | 1.000| 2.000          | 10.000         | 30.000 |
|-------------------------------------|-------------------|------|--------|-----------|------|----------------|-----------------|------|
| Panel B: Subsample from 1980–1997   |                   |      |        |           |      |                |                 |      |
| Coupon Rate (%)                     | 701               | 8.562 | 2.685  | 8.000     | 3.875| 5.750          | 12.625          | 16.250 |
| Issue Size (million $)              | 701               | 9694.285 | 5134.668 | 9496.000 | 627.000| 3123.000      | 17,527.000     | 23,360.000 |
| Maturity (years)                    | 701               | 6.081 | 6.420  | 4.000     | 1.000| 2.000          | 10.000         | 30.000 |
|-------------------------------------|-------------------|------|--------|-----------|------|----------------|-----------------|------|
| Panel C: Subsample from 1998–2016   |                   |      |        |           |      |                |                 |      |
| Coupon Rate (%)                     | 906               | 3.435 | 2.875  | 2.575     | 0.125| 0.625          | 6.500           | 15.750 |
| Issue Size (million $)              | 906               | 24,635.622 | 25,143.000 | 9534.726 | 1501.000| 12,398.000    | 36,042.000     | 45,489.000 |
| Maturity (years)                    | 906               | 7.038 | 5.000  | 7.610     | 1.000| 2.000          | 20.000         | 30.000 |

Table 2
Descriptive statistics of total month-end idiosyncratic pricing.
This Table reports the descriptive statistics of month-end idiosyncratic pricing results from the LP model. Total Month-end Idiosyncratic Pricing is the theoretical arbitrage profits, in dollar, achievable in a frictionless market at the end of each month based on the LP model. Number of Treasuries is the number of T-notes and T-bonds at the end of each month in the feasible set of the LP Model. Idiosyncratic Pricing per Treasury is the Total Month-end Idiosyncratic Pricing divided by the Number of Treasuries. Both measures of idiosyncratic pricing assume $100 par value of each Treasury security.

| Number of months | Total Month-end Idiosyncratic Pricing ($) | Mean | Median | Std. Dev. | Min. | 10th Percentile | 90th Percentile | Max. |
|------------------|-------------------------------------------|------|--------|-----------|------|----------------|-----------------|------|
| 444              | 16,512                                    | 16,512| 14,530 | 13,468    | 0.340| 2.190          | 34,340          | 84,080 |
| Idiosyncratic Pricing per Treasury ($) | 444                               | 0.106 | 0.077  | 0.103     | 0.003| 0.012          | 0.222          | 0.719 |
| Number of Treasuries | 444                               | 175,671 | 169.000 | 51,969    | 91.000| 117,000        | 268,000        | 305,000 |

2.1. Data collection and sample descriptive statistics

The CRSP Daily Treasury data from 1980 to 2016 are used as the data source. The sample includes all non-callable, non-flower, fixed coupon and fixed principal US T-notes and T-bonds. Several types of Treasury securities are excluded: inflation protected securities (TIPS), when-issued securities, Treasury strips and T-bills. The quoted bond prices are adjusted for accrued interest. Besides prices, the CRSP bond data file is the source of the total amount of each bond outstanding, the coupon rate, and the maturity.

Table 1 reports the descriptive statistics of the Treasury securities used in the study. Over the whole sample, there are a total of 1422 T-notes and T-bonds with an average coupon rate of 5.472%. The average issue size is about $18.7 billion and average maturity is about 6 years. Panels B and C report descriptive statistics for the 1980–1997 and 1998–2016 subsample periods. Treasuries included in the latter half of the sample period are noticeably larger in issue sizes and lower in coupon rates. In addition, there are more T-notes and T-bonds in the second half of the sample period.\[1\]

\[1\] Flower bonds, also known as estate tax anticipation bonds, became immediately redeemable at the par value plus accrued interest upon the death of bondholders for the purpose of paying estate tax. This unique feature made flower bonds particularly appealing to some investors (Mayers and Smith, 1987). As a result, we exclude flower bonds in our sample. Flower bonds were issued by the US Treasury until 1971. The last one matured in 1998. Before 1985, the US Treasury issued some callable bonds.

2.2. Descriptive statistics

Table 2 reports the descriptive statistics for the monthly LP results. The sample average Number of Treasuries (i.e., the number of T-notes and T-bonds each month in the feasible set of the LP model) is 176 with a minimum of 91 and maximum of 305. The mean (median) Total Month-end Idiosyncratic Pricing for the whole sample period is $16.51 ($14.53) with a standard deviation of $13.47. Given the large number of T-notes and T-bonds, the Idiosyncratic Pricing per Treasury, defined as the Total Month-end Idiosyncratic Pricing divided by the month-end Number of Treasuries, provides a better sense of the magnitude of the idiosyncratic pricing. The mean (median) Idiosyncratic Pricing per Treasury is $0.106 ($0.077) per $100 par value with a standard deviation of $0.103. As a comparison, the mean (median) bid-ask spread for the Treasury securities during the sample period is $0.078 ($0.063). Thus, the average Idiosyncratic Pricing per Treasury is about 130% of the average bid-ask spread.\[12\]

2.3. Intertemporal variations in idiosyncratic pricing

As discussed in Section 3, several reforms and institutional developments since 1980 might have reduced market frictions, increased the homogeneity of US Treasury securities, and lowered costs to arbitrage. Thus, aggregate idiosyncratic pricing is likely to have declined over the sample period. To examine the intertemporal variations in idiosyncratic pricing, we divide the whole sample ...
into eight subsamples of 60 months each, except the 2015–2016 subsample period. Table 3 reports the subsample means of the two measures of idiosyncratic pricing.

The average Total Month-end Idiosyncratic Pricing was $25.59 during the 1980–1984 subsample period. This measure of idiosyncratic pricing was halved a decade later to $14.15 during the 1990–1994 subsample period and has remained at around $10 since 2010. During the 1980–1984 period, the Idiosyncratic Pricing per Treasury was $0.25. It dropped to $0.03 in the two most recent years. The decline in the Idiosyncratic Pricing per Treasury was even more dramatic because the number of securities increased substantially.

Two other interesting patterns emerge from Table 3. First, the decreases in idiosyncratic pricing were very steep from 1980 to 1994 but have become more gradual since then. This pattern is consistent with the fact that most market efficiency-enhancing reforms and institutional developments occurred from 1980 to 1994, including the Tax Reform Act of 1986 and the introduction of the Treasury STRIPS program, as detailed in Section 3.

Second, the declines in idiosyncratic pricing over time are not monotonic and there are two sub-periods (1995–1999, and 2005–2009) where it increased from the previous sub-period. The 1995–1999 period experienced the Asian and Russian financial crises as well as the collapse of Long-Term Capital Management. The 2005–2009 time period overlapped significantly with the recent global financial crisis. An extensive literature suggests that financial crises are often coupled with disruptions in financial intermediation and increases in financial market frictions.13

To further investigate if the increase in idiosyncratic pricing is related to financial crises, we plot the five-month moving averages of the two month-end measures of idiosyncratic pricing over the sample period in Figs. 1 and 2.14 The two plots show a clear downward trend in Treasury idiosyncratic pricing, particularly from the 1980 to early 1990s, consistent with the pattern observed in Table 3.

There is indeed a significant spike in both measures of idiosyncratic pricing during late 2008 and early 2009. However, the spike is quite short-lived, and the level of idiosyncratic pricing came

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13 Gertler and Kiyotaki (2010), Hu et al. (2013) and Musto et al. (2018).

14 To smooth out month-to-month volatility, we plot the 5-month moving averages of the two measures of idiosyncratic pricing.
back down quickly. Hu et al. (2013) and Musto et al. (2018) document a similar jump in Treasury idiosyncratic pricing during the 2007–2009 financial crisis. Hu et al. (2013) present evidence that severe lack of risk-arbitrage capital during the crisis period kept potential arbitrageurs from exploiting significant idiosyncratic pricing. On the other hand, Musto et al. (2018) argue that heterogeneous investors’ preference for liquidity drives the spike in idiosyncratic pricing. Both explanations suggest increased market frictions and impediments to arbitrage during the financial crisis, supporting our basic premise that the LP-based approach captures the aggregate effects of market frictions and limits/costs to arbitrage on the relative pricing of US Treasury securities.

For the 1995–1999 time period, there was no similar spike in idiosyncratic pricing, but its level seemed to be elevated at the peak of Asian and Russian financial crises in 1998.

2.4. Idiosyncratic pricing and portfolio size

Idiosyncratic pricing identified by the LP model represents theoretical arbitrage profits that can be exploited by arbitrageurs in a friction-less market without any limitations to arbitrage. Furthermore, the LP model assumes that 100% of the short proceeds can be used to finance the long positions, resulting in a zero-cost long-short portfolio. In the real world, however, margin requirements force arbitrageurs to commit capital for their arbitrage portfolios.

To put the potential arbitrage profits into the perspective of capital requirements, we calculate the values of the monthly short portfolios identified by the LP model. Specifically, we multiply the LP Short Weight of each security by its bid price to get the value of each shorted security. Then we add up the values of all shorted securities to get the total value of the Short Portfolio. Fig. 3 plots the values of the monthly Short Portfolios over time.

The sizes of the Short Portfolios fluctuate between $1000 to $4000 from 1980 to 2000. However, they increase significantly after 2010 to $6000 in more recent years. An arbitrageur could, theoretically, earn an arbitrage profit of $25 on a short portfolio of $2000 in the 1980s. Fast forward to 2016, an arbitrageur needs to construct a short portfolio of $6000 to squeeze out a paltry profit of $10, or a short portfolio of $15,000 to earn a profit of $25. This suggests greater pricing efficiency and lower barriers to arbitrage in more recent years.

2.5. Persistence in idiosyncratic pricing

The LP model is designed to detect any idiosyncratic pricing, whether due to transient factors or inherent and persistent factors. An alternative explanation for the large decline in idiosyncratic pricing over the last four decades is large decreases in transient factors. For example, lower liquidity in the early years may have caused prices of some Treasury securities to temporarily deviate from their fundamental values because of short-term imbalances in buy and sell orders. This transient-factor hypothesis suggests that idiosyncratic pricing is random and can be arbitrated away quickly. High idiosyncratic pricing at the end of a given month might attract more arbitrage trading in the following trading days which would result in reduction in the idiosyncratic pricing. In addition, the idiosyncratic pricing identified by the LP model could also be a result of errors in reported prices, particularly for the earlier sample period. Erroneously reported prices of some Treasury securities could result in large LP Idiosyncratic Pricing and corrections of the reported price errors in the following trading days would reverse the idiosyncratic pricing. This explanation also suggests that the documented decline in idiosyncratic pricing over the last four decades could be a result of improved data quality and more accurately reported Treasury prices over time.

On the other hand, if the idiosyncratic pricing is a manifestation of some inherent hard-to-arbitrage-away market frictions or unique features, High-Priced (Low-Priced) securities would tend to remain High-Priced (Low-Priced) over time. In other words, the idiosyncratic pricing should be persistent. We call this the persistent-factor hypothesis.

To distinguish these two hypotheses, we examine idiosyncratic pricing on a daily basis, based on the previous month-end LP Long

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15 Results based on the value of Long Portfolio are essentially identical. Indeed, the difference between the Long and Short Portfolio is the monthly aggregate idiosyncratic pricing.

16 The large short portfolio sizes in more recent years are driven by the large number of securities being shorted by the LP model. The smaller monthly aggregate idiosyncratic pricing combined with a large number of shorted securities indicates that the idiosyncratic pricing per shorted security decreased dramatically in recent years.
and Short Weights. Since all US T-notes and T-bonds in our sample mature either at the end or the middle of the month, there is no change in the composition of T-notes and T-bonds from the end of the month when the LP is run through the following 10 trading days. To detect the potential persistence in idiosyncratic pricing, we multiply the previous month-end LP weights by the subsequent daily price of each respective Treasury security and sum up the products as in the following equation:

\[ M_{k,i} = \sum_{j=1}^{H} (x_{jk}^h p_{jk}^h) - \sum_{j=1}^{H} (x_{jk}^p p_{jk}^p) \]  

(6)

where \( H \) is the Number of Treasury securities, \( x_{jk}^h \) (\( x_{jk}^p \)) is bond j’s Short Weight (Long Weight) from the LP model at the end of month k. \( p_{jk}^h \) (\( p_{jk}^p \)) is the bid (ask) price of bond j at the ith trading day after the end of month k. Thus, \( M_{k,i} \) measures the total idiosyncratic pricing at the ith trading day after the end of month k. Finally, to adjust for the size of the overall market, we scale \( M_{k,i} \) by H to get the per-Treasury daily idiosyncratic pricing, \( D_{k,i} \).

\[ D_{k,i} = M_{k,i} / H \]  

(7)

The transient-factor hypothesis implies that \( D_{k,i} \) would quickly converge to zero or even turn negative as (1) idiosyncratic pricing is arbitrated away, (2) reported pricing errors are corrected, (3) High-Priced securities at the end of month k might become less High-Priced or even Low-Priced at date \( k+i \), and vice versa. On the other hand, the persistent-factor hypothesis predicts that \( D_{k,i} \) will remain positive and relatively constant over time, i.e., expensive (cheap) securities remain expensive (cheap).

Panel A of Table 4 reports the empirical results for the whole sample period. Trading Day 0 represents the end of each month and Trading Days 1 to 10 are the first to the 10th trading days of the following month. The statistics for Trading Day 0 are LP results, already reported earlier but reproduced in the Table for easy comparison. The statistics for Trading Days 1 to 10 are based on Eq. (7).

The average Idiosyncratic Pricing per Treasury decreases from $0.106 at the month end to $0.081 on the first trading day of the following month, suggesting that about 24% of the LP Idiosyncratic Pricing is transient. The idiosyncratic pricing decreases slowly over the next nine trading days to $0.064 by day 10. The standard deviations of daily idiosyncratic pricing are much larger than that of the Month-end Idiosyncratic Pricing. Even so, the 10th percentile of the daily idiosyncratic pricing remains positive until the ninth trading day.

To examine the robustness of the patterns observed above, panels B and C report the empirical results for two subsample periods: the 1980–1984 and the 2000–2004 periods. Similar patterns of persistent idiosyncratic pricing are observed for both subsample periods, even though their initial Month-end Idiosyncratic Pricing differs significantly. One noticeable difference, however, is that the component of transient idiosyncratic pricing in the early sample period is much smaller, accounting for less than 5% of the Idiosyncratic Pricing per Treasury. On the other hand, for the 2000–2004 subsample period, the transient idiosyncratic pricing accounts for more than 40% of the Idiosyncratic Pricing per Treasury. This finding suggests that reduced market frictions and impediments to arbitrage in more recent years make idiosyncratic pricing easier to be arbitrated away.

Overall, the empirical results suggest that the majority of the idiosyncratic pricing identified by the LP model at the month end is persistent and hard to arbitrage away, consistent with the persistent-factor hypothesis.

2.6. Robustness checks

Numerous studies have documented the on-the-run effect for the relative pricing of US Treasuries. A natural question is to what extent the on-the-run effect contributes to the overall Treasury market idiosyncratic pricing. To answer this question, we remove

\footnote{17} Note that we do not run the LP model on a daily basis. We could not infer whether the idiosyncratic pricing from daily runs of LP model is driven by the same set of High-Priced or Low-Priced securities overtime. In other words, we could not determine the persistence or transience in idiosyncratic pricing of individual securities overtime with daily LP model runs.

\footnote{18} The two subsample periods have the highest and lowest Total Month-end Idiosyncratic Pricing respectively as reported in Table 3. Empirical results from other subsample periods are similar and, for brevity, not reported.
Table 4
Daily Idiosyncratic Pricing.
This Table reports the statistics for daily idiosyncratic pricing. Trading Day 0 represents the end of each month and Trading Days 1 to 10 are the first to the tenth trading days of the following month. The statistics for Trading Day 0 are the Month-end Idiosyncratic Pricing per Treasury from the LP model. The statistics for Trading Days 1 to 10 are based on Eq. (7). Panel A reports the statistics for the whole sample period, Panel B for the 1980–1984 subperiod and Panel C for the 2000–2004 subperiod.

| Trading day | Mean | Median | Std. Dev. | 10th Percentile | 90th Percentile |
|-------------|------|--------|-----------|----------------|----------------|
| Panel A: Whole Sample Period |
| 0 | 0.106 | 0.077 | 0.103 | 0.012 | 0.224 |
| 1 | 0.081 | 0.066 | 0.183 | 0.001 | 0.245 |
| 2 | 0.080 | 0.064 | 0.183 | 0.002 | 0.246 |
| 3 | 0.079 | 0.066 | 0.182 | 0.001 | 0.245 |
| 4 | 0.079 | 0.064 | 0.182 | 0.001 | 0.238 |
| 5 | 0.079 | 0.064 | 0.182 | 0.000 | 0.237 |
| 6 | 0.079 | 0.063 | 0.182 | 0.000 | 0.241 |
| 7 | 0.078 | 0.063 | 0.183 | 0.000 | 0.239 |
| 8 | 0.077 | 0.062 | 0.182 | 0.000 | 0.239 |
| 9 | 0.075 | 0.062 | 0.185 | −0.005 | 0.228 |
| 10 | 0.064 | 0.047 | 0.195 | −0.013 | 0.213 |
| Panel B: 1980 to 1984 Subsample Period |
| 0 | 0.251 | 0.212 | 0.141 | 0.100 | 0.473 |
| 1 | 0.244 | 0.205 | 0.141 | 0.100 | 0.467 |
| 2 | 0.242 | 0.204 | 0.140 | 0.098 | 0.466 |
| 3 | 0.240 | 0.204 | 0.138 | 0.090 | 0.453 |
| 4 | 0.238 | 0.200 | 0.140 | 0.092 | 0.455 |
| 5 | 0.236 | 0.206 | 0.140 | 0.090 | 0.451 |
| 6 | 0.237 | 0.202 | 0.142 | 0.083 | 0.448 |
| 7 | 0.235 | 0.205 | 0.146 | 0.086 | 0.445 |
| 8 | 0.229 | 0.195 | 0.149 | 0.079 | 0.447 |
| 9 | 0.215 | 0.181 | 0.160 | 0.049 | 0.455 |
| 10 | 0.217 | 0.181 | 0.180 | 0.039 | 0.454 |
| Panel C: 2000 to 2004 Subsample Period |
| 0 | 0.054 | 0.034 | 0.048 | 0.008 | 0.141 |
| 1 | 0.032 | 0.026 | 0.143 | 0.002 | 0.139 |
| 2 | 0.032 | 0.026 | 0.143 | 0.002 | 0.139 |
| 3 | 0.032 | 0.025 | 0.142 | 0.001 | 0.137 |
| 4 | 0.032 | 0.025 | 0.142 | 0.001 | 0.138 |
| 5 | 0.032 | 0.027 | 0.142 | 0.002 | 0.138 |
| 6 | 0.031 | 0.026 | 0.142 | 0.001 | 0.139 |
| 7 | 0.032 | 0.026 | 0.143 | 0.001 | 0.139 |
| 8 | 0.032 | 0.026 | 0.143 | 0.001 | 0.142 |
| 9 | 0.031 | 0.026 | 0.143 | −0.003 | 0.140 |
| 10 | 0.040 | 0.022 | 0.177 | −0.005 | 0.137 |

Table 5
Robustness checks.
This Table reports the results from seven robustness checks. The second column reproduces the main results from Table 2. The third column reports the results when on-the-run Treasuries are excluded from the LP model. The fourth column reports the results when Treasury securities with daily price runs are excluded. The fifth column reports the results when the largest potential outlier is excluded from each monthly LP model. The sixth column reports the results when old 30-year T-bonds with less than 10 years left to maturity are excluded. The seventh column reports the results when all 30-year T-bonds are excluded. The second last column reports the results when the bid-ask spread for each Treasury security is increased by 100%. The last column reports the results when the linear programming model assumes that all securities can be bought or sold at the average bid and ask prices, or zero bid-ask spread.

| | Whole sample | Exclude on-the-run issues | Exclude price-run issues | Exclude outliers | Exclude old 30-year T-Bonds | Exclude all 30-year T-Bonds | Double Bid/Ask | Midpoint Bid/Ask |
|-----------------|----------------|--------------------------|------------------------|-----------------|-----------------------------|-----------------------------|---------------|----------------|}
| Total Month-end Idiosyncratic Pricing |
| 16.512 | 14.925 | 14.601 | 13.844 | 14.910 | 14.607 | 14.656 | 17.291 |
| Idiosyncratic Pricing Per Treasury |
| 0.106 | 0.088 | 0.102 | 0.088 | 0.097 | 0.105 | 0.093 | 0.111 |
| Number of Treasuries |
| 175.671 | 170.275 | 163.429 | 174.671 | 170.851 | 145.977 | 175.671 | 175.671 |

all the on-the-run issues from the feasible set and re-run the LP model every month. The Total Month-end Idiosyncratic Pricing and Idiosyncratic Pricing per Treasury without the on-the-run issues are reported in the third column of Table 5. Column two reproduces the results for the whole sample in Table 2 for ease of comparison.

The Total Month-end Idiosyncratic Pricing (Idiosyncratic Pricing per Treasury) without the on-the-run issues is $14.925 ($0.088). Thus, about 90% of the aggregate idiosyncratic pricing is not due to the on-the-run effect. That said, the on-the-run effect is salient. On average, there are about 5 on-the-run issues each month, or about 3% of the total number of Treasuries, but they account for about 10% of the aggregate idiosyncratic pricing.

There is a concern about possible stale prices in the CRSP bond data. As noted by prior research, some old T-notes and T-bonds...
may not trade often in the secondary market and the quoted prices from CRSP might not be actual tradeable prices. For example, Sarig and Warga (1989) find a significant percentage (2% to 10%) of CRSP Treasury price quotes at the end of month exactly matches the quotes at the end of the previous month from 1926 to 1985. The authors call these price runs.

To address this concern, we check the end-of-month price quotes against the price quotes on the previous trading date. On average, about 8% of quotes represent daily price runs.\textsuperscript{20} The LP model is re-run without Treasuries with daily price runs in the feasible set. The results are reported in the fourth column of Table 5. The Total Month-end Idiosyncratic Pricing (Idiosyncratic Pricing per Treasury) decreases slightly to $14.601 ($0.102) after exclusion of Treasury securities with a daily price run. Thus, our results are not significantly affected by potentially stale prices.

In addition to stale prices, there is a concern about outsized influences of large outliers on idiosyncratic pricing. To address this concern, we first identify potential outliers and then re-estimate idiosyncratic price by excluding the largest potential outlier each month. Specifically, we run the LP model H times every month, where H is the number of securities in the feasible set each month. With each run of the LP model, we exclude one security at a time from the feasible set and find the aggregate idiosyncratic pricing based on the H-1 securities. The difference between the LP Idiosyncratic Pricing based on the H securities and that based on the H-1 security is the marginal contribution to the aggregate idiosyncratic pricing by the excluded security, which we term marginal idiosyncratic pricing. We designate the security with the largest marginal idiosyncratic pricing each month as a potential outlier because it has the largest impact on the aggregate idiosyncratic pricing of the month. The monthly idiosyncratic pricing is then re-estimated after excluding the largest potential outlier. The mean idiosyncratic pricing excluding potential outliers is reported in the fifth column of Table 5. The Total Month-end Idiosyncratic Pricing (Idiosyncratic Pricing per Treasury) decreases to $13.844 ($0.088). While the idiosyncratic pricing does decrease by design, our main results are not significantly affected by potential large outliers.

Musto et al. (2018) find large price differentials between T-notes and 30-year T-bonds with less than 10 years left to maturity. To make sure our main results are not solely driven by the documented pricing anomaly of old bonds, we remove old 30-year T-bonds with less than 10 years left to maturity from the feasible set. The results are reported in the sixth column of Table 5. The Total Month-end Idiosyncratic Pricing (Idiosyncratic Pricing per Treasury) decreases to $14.910 ($0.097), consistent with the findings of Musto et al. (2018). However, our main results are not driven solely by the pricing anomaly of old T-bonds.

Some previous studies based on yield-curve fitting models exclude 30-year T-bonds due to difficulty in estimating long-term yields (see, for example, Hu et al., 2013). To check if our main results are robust to the exclusion of all 30-year T-bonds, we re-run the LP model without 30-year T-bonds in the feasible set and report the results in the seventh column of Table 5. The Total Month-end Idiosyncratic Pricing decreases to $14.607, but Idiosyncratic Pricing per Treasury remains largely unchanged.

The LP model assumes that an arbitrager can trade at the bid or ask price without moving the market. Large buy or sell orders can possibly move the prices, making some potential arbitrage impractical. To address this, we artificially increase the quoted bid-ask spread by 100%. The implicit assumption is that a buy (sell) order will push the price higher (lower) by 50% of the quoted spread. This approach takes into consideration the relation between liquidity and price impacts since less liquid bonds tend to have both large bid-ask spreads and high price impacts.

The empirical results based on inflated bid-ask spreads are reported in the second to last column of Table 5. The Total Month-end Idiosyncratic Pricing (Idiosyncratic Pricing per Treasury) decreases to $14.656 ($0.093). Wider bid-ask spreads lower potential arbitrage profit. However, their impact is fairly limited. Thus, our main empirical results are robust to potential price impacts of large trades.

Finally, there is a concern with the validity and accuracy of the bid/ask spread reported in the CRSP Treasury database (Adrian et al., 2017; Duffee, 1996). The results based on artificially inflated bid-ask spread suggest our main findings are robust to possible downward bias in the reported bid/ask spread. To assess the sensitivity of the results to possible upward bias, i.e., reported bid/ask spreads too wide, we have also run the LP model with the average bid and ask prices, effectively assuming zero bid/ask spread and estimating the upper bound on idiosyncratic pricing. Not surprisingly, the magnitude of idiosyncratic pricing is larger; the Total Month-end Idiosyncratic Pricing (Idiosyncratic Pricing per Treasury) increases to $17.291 ($0.111) as reported in the last column of Table 5. However, the pattern of secular decline in idiosyncratic pricing is robust.\textsuperscript{21}

3. Changes in the tax law and institutional developments since 1980

The empirical results reported in the previous section show a very large decrease in the theoretical arbitrage profit from 1980 to 2016, implying reductions in market frictions. This section first describes significant changes in the Treasury bond market since 1980 that are likely to reduce unique features and lower costs of arbitrage. Then, using two time-series regression models, we empirically test the impact of these changes on idiosyncratic pricing.

3.1. Expansion of the US treasury market

Since the 1980s, the US federal government has been running sizable deficits resulting in the US Treasury borrowing very large amounts of money. To meet these borrowing needs the US Treasury has increased both the issuing frequency and issue size of new securities. Fig. 4 illustrates the increases in the size of the long-term marketable Treasury security market. Panel A shows the number of non-callable, non-flower, fixed coupon and fixed principal T-notes and T-bonds and the total amount of par value outstanding at the end of each month from 1980 to 2016. There has been a steady increase in the number of Treasury securities except for the years between the late 1990s to early 2000s, a period when the US Federal Government had fiscal surpluses. Similarly, the total size of the market, in terms of the dollar amount outstanding, has increased dramatically since 1980. Panel B reports the average amount outstanding per Treasury note or bond. McCauley and Rebolona (2000) present evidence that liquidity of government bond markets increases with the total market size. Thus, the significant increases in both the total market size and the size of individual Treasury securities likely have led to substantial improvements in market liquidity over the last four decades.

In addition, the large increase in the size of Treasury issues combined with the increase in the number of securities with the same maturities and different coupon levels has increased the opportunities for large institutional bond investors to switch from a

\textsuperscript{20} We also checked for monthly price runs for our sample and find them much rarer, at less than 1%, than that documented by Sarig and Warga (1989), suggesting great improvement in the liquidity of the US Treasury market.

\textsuperscript{21} For the sake of brevity, we do not present the intertemporal variations in the upper bounds of Idiosyncratic Pricing, but they are available upon request.
relatively high-priced security to a similar, but more attractively priced security. With a large number of securities available, bond investors (who typically hold portfolios of bonds) can examine the bonds in their portfolio and use LP model to find whether some bonds in their portfolio should be switched for other bonds with the same or higher future cash flows for a lower total cost (Durand, 1999; Hodges and Schaefer, 1977, and Ronn, 1987). The consequence of portfolio switching by large institutions is the downward (upward) price adjustment of bonds with relatively high (low) prices, similar to risk-free arbitrage. Thus, portfolio switches by institutions and individuals can help to reduce idiosyncratic pricing.

3.2. Increase in market liquidity

Consistent with the increased sizes of both the total Treasury security market and individual Treasury securities, Treasury market liquidity has increased significantly. Adrian et al. (2017) report that trading volume, trading frequency and average trade size for the 2-year, 5-year and 10-year on-the-run Treasury securities increased 2 to 8 times from the 1991–2000 sample period to the 2001–2017 sample period. In addition, the average bid-ask spreads and market price impacts have decreased significantly, and the market depth has increased by a factor of 3 to 10 between the two sub-sample periods.22 This is consistent with the empirical findings by Fleming (2002) that liquidity improves with issue size. Increased liquidity and lower transaction costs increase the potential for arbitrage and likely contribute to decreasing idiosyncratic pricing.23

3.3. Tax Reform Act of 1986

Prior to the 1986 Tax Reform Act, discounts on market discount bonds were treated as capital gains at the maturity or disposal of the bonds. This created two tax advantages for discount T-notes and T-bonds. First, the market discount was taxed at the lower capital gain tax rate. Second, the tax on the discount was deferred until the disposal or maturity of the bond. The Tax Reform Act of 1986 significantly reduced the preferential tax treatment of discount bonds. For discount bonds issued after July 18, 1984 or issued on or before that date but purchased after April 30, 1993, the market discount is treated as interest income and taxed at the ordinary income rate. While investors still have the option to defer the income tax on market discounts until the disposal or maturity of the bond, the change in the asymmetric tax treatment of discount and premium bonds has significantly diminished the appeal of discount bonds and likely has reduced idiosyncratic pricing of discount bonds.

3.4. Increased holdings by potentially tax-exempt institutional investors

Over the last four decades, there has been a significant increase in the holdings of marketable Treasury securities by potentially tax-exempt institutions. Fig. 5 depicts the percentages of marketable US Treasury securities owned by foreign institutions, state and local governments, and pension funds.24 State and local governments as well as pension funds are exempt from federal income tax. The majority of foreign holdings of US Treasuries are by foreign official institutions which are exempt from US federal income tax. The 2015 Report on Foreign Portfolio Holdings of US Securities shows that about 70% (60%) of foreign holdings of long-term US Treasuries (Treasury bills) are by foreign official institutions from 2008 to 2015 (Tables 10 and 11 on page 15). Similar patterns are observed in the earlier years.25

As shown in Fig. 5, potentially tax-exempt investors held less than one third of privately-owned US Treasury securities in the

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22 The average bid-ask spreads of all T-notes and T-bonds in the CRSP database exhibit similar downward trend from the 1980s to the present.

23 Several studies have shown that higher liquidity helps to improve price efficiency in the equity, credit and option markets (Chordia et al., 2008, Nashikkar et al., 2011, Devile and Riva, 2007).

24 Holdings by the Federal Reserve are excluded from the numerator and denominator. We obtain the Treasury holdings data from various issues of the US Treasury Bulletin.

25 Detailed data on holdings by foreign official institutions are not available prior to 2000. However, the 2003 Report indicates the percentages of holdings by foreign official institutions are relatively stable from early 1980s to the present at about 60% (Table 10 on page 18).
early 1980s. The percentage increased to about 50% by the mid-1990s and stayed close to 70% in more recent years. It is very plausible that the Tax Reform Act of 1986 and the increased participation of tax-exempt investors in the US Treasury market have reduced significantly or even completely eliminated price distortions from tax effects. Indeed, Green and Odegaard (1997) find the tax effect on Treasury pricing disappears after 1986 and the implicit marginal tax rate for a ‘representative’ investor in the US Treasury market became close to zero.

3.5. Introduction and growth of Treasury STRIPS

In 1985, the US Treasury began the practice of allowing stripping of Treasury securities by book entry in the STRIPS (Separate Trading of Registered Interest and Principal of Securities) program, i.e., trading of the coupons and principals of some T-notes and T-bonds separately as zero-coupon Treasury strips. Reconstitution of strips was initiated in 1987. All 10-year T-notes and T-bonds issued after November 15, 1984 were eligible for the STRIPS program either upon their original issuance or after their first interest payment date. Between 1987 and 1997, many strippable 10-year T-notes and T-bonds were issued and the total par value of Treasury securities held in stripped form increased steadily. All marketable fixed-rate T-notes and T-bonds issued on and after September 30, 1997 are strippable (Bulter et al., 2014).

The Treasury STRIPS program increases the number of investment choices and makes portfolio improvements more feasible for institutional bond investors. With sufficient supplies of strips, Treasury security dealers can rapidly complete arbitrage transactions between strips and coupon bearing Treasuries at minimal cost. If the market price of a bond is higher (lower) than the market price of a portfolio of strips with the same pre-tax cash flows, dealers can strip the bond and sell its cash flows as individual strips (reconstitute the strips and sell it as a bond). Indeed, Jordan et al. (2000) find potential arbitrage profits between coupon-bearing Treasury securities and their corresponding portfolios of strips are rare and generally not statistically significant, indicating a great integration of the two markets.

3.6. Empirical tests

To better understand the secular decline in idiosyncratic pricing over the sample period, this section empirically tests factors that determine the idiosyncratic pricing using two time-series regression models. In the first (second) model, the dependent variable is the Total Month-end Idiosyncratic Pricing (Idiosyncratic Pricing per Treasury). Following the previous discussion, we hypothesize that the 1986 Tax Reform Act, Treasury issue size, number of Treasury securities, market liquidity, growth of the Treasury strips market, and holdings by potentially tax-exempt investors are major factors contributing to the decline in idiosyncratic pricing of US Treasury securities. Thus, both regression models include the following explanatory variables.

1. Post-Tax-Reform Dummy. The variable is set equal to 1 for years after 1986 and 0 otherwise. As the 1986 tax law change reduced the preferential treatment of discount bonds, we expect the coefficient on the dummy to be negative in both regressions.

2. Log Average Issue Size. The variable is defined as the logarithm of the average size of T-notes and T-bonds included in the feasible set of the monthly LP model. We expect the coefficient on this variable to be negative in both regressions.

3. Log Number of Issues. The variable is defined as the logarithm of the number of Treasury securities in the LP feasible set every month. Since a larger number of Treasuries makes arbitrage easier, we expect the coefficient on this variable to be negative in the Idiosyncratic Pricing per Treasury regression. However, a larger number of Treasuries also increases the potential for a greater aggregate amount of idiosyncratic pricing. Thus, the impact of this variable on the Total Month-end Idiosyncratic Pricing is an empirical question.

4. Fraction in Stripped Form. The variable is defined as the percentage of T-notes and T-bonds held in stripped form at the end of each month. The variable is set to 0 for months prior to the introduction of the Treasury STRIPS program.
from the Monthly Statement of the Public Debt. As an active market of Treasury strips makes arbitrage easier, we expect the coefficient on this variable to be negative.

5) Fraction of Tax-exempt Holdings. The variable is defined as the percentage of marketable Treasuries held by potentially tax-exempt institutions. As increased holdings by tax-exempt institutions may reduce price distortions from differential tax treatments, we expect the coefficient on this variable to be negative.

6) On-Run-Premium. This variable is a proxy for overall market liquidity and defined as the difference between the model implied yield and the actual yield to maturity of the on-the-run 10-year T-note in basis points.27 When market liquidity is low, investors would pay a price premium (or accept a lower yield) to hold the more liquid on-the-run issues, resulting in higher on-the-run premiums. Hu et al. (2013) and Adrian et al. (2017) show that the On-Run-Premium increased significantly during market liquidity crises.28 Thus, On-Run-Premium is used extensively in the literature to proxy for Treasury market liquidity. To avoid a mechanical relation between the On-Run-Premium and idiosyncratic pricing, the dependent variables are idiosyncratic pricing excluding all on-the-run issues from the LP feasibility sets. As lower market liquidity makes arbitrage more costly and difficult to implement, we expect the coefficient on this variable to be positive, i.e., when on-the-run premium is high, idiosyncratic pricing is expected to be high as well.

Table 6 reports the empirical results from the two time-series regression models. Most explanatory variables have the expected signs except the Fraction of Tax-exempt Holdings, which is not significant. The coefficient on Log Number of Treasuries is significantly positive in the Total Month-end Idiosyncratic Pricing regression, but insignificant in the Idiosyncratic Pricing per Treasury regression. This finding suggests that a larger number of Treasuries does not reduce average idiosyncratic pricing but increases the aggregate amount of idiosyncratic pricing. The coefficients on Log Average Issue Size, Post-Tax-Reform Dummy, and the On-Run-Premium are statistically significant at the 5% or 1% level in both regressions, suggesting that these are important factors contributing to the secular decline in idiosyncratic pricing in the US Treasury market.

To gauge how well the regression models can explain the secular decline in idiosyncratic pricing, we retrieve the regression predicted idiosyncratic pricing, both aggregate and per security, and plot them over time in Fig. 6. A comparison of the two graphs with Figs. 1 and 2 of the actual idiosyncratic pricing shows a remarkable similarity in overall trend over time. The regression predicted idiosyncratic pricing clearly exhibits a downward trend over the sample period as well as a sharp spike during the 2008–2009 financial crisis. This suggests the parsimonious regression models capture the intertemporal variations in idiosyncratic pricing very well.

4. Idiosyncratic pricing at the micro-level

The previous section examines idiosyncratic pricing in the US Treasury market at the macro-level and documents a secular decline in idiosyncratic pricing from 1980 to 2016. This section focuses on the idiosyncratic pricing at the individual Treasury security level by examining the monthly LP Long and Short Weights of all securities in the LP feasible set. The sample analyzed in this section consists of security-month observations.

4.1. Distribution of long and short weights

To gauge the extent of idiosyncratic pricing for individual Treasury securities, we plot the frequency distribution of the LP Long and Short Weights in Fig. 7. The LP weights are sorted into 23 weight buckets by an increment of 0.1. Securities with LP Short Weights (Long Weights) of 1 fall into Bucket −1 (1). Bucket 0 includes securities that are neither bought nor shorted in the LP model. Securities in the (−1, −0.9] bucket have LP Short Weights greater than or equal to 0.9 but less than or 1, etc.

The histogram shows a tri-modal distribution of the LP Weights. Close to half of the sample are neither bought nor shorted, implying no idiosyncratic pricing. In addition, about 23% of securities have Long or Short LP weights less than 0.1. At the two ends, about 28% of securities have Long Weights or Short Weights greater than or equal to 0.8. Less than 2% of securities have LP weights, long or short, between 0.1 and 0.8. The tri-modal distribution of the LP Weights (also documented by Ronn (1987)) suggests that idiosyncratic pricing is concentrated in about 30% of the Treasury security-month observations.

### Table 6

Determinants of Idiosyncratic Pricing.

This Table reports results of two time-series regressions of monthly idiosyncratic pricing. The dependent variable for the first model is the Total Month-end Idiosyncratic Pricing (excluding on-the-run issues) and the dependent variable for the second model is the Idiosyncratic Pricing per Treasury (excluding on-the-run issues). Post-Tax Reform Dummy is set to 1 for years after 1986 and 0 otherwise. Log Average Issue Size is the logarithm of the average size of T-notes and T-bonds. Log Number of Issues is the logarithm of the number of Treasury in the LP feasible set every month. On-Run-Premium is the difference between the actual yield to maturity of the on-the-run 10-year T-notes and the model implied yield in basis points. Fraction in Stripped Forms is the percentage of T-notes and T-bonds held in stripped form at the end of each month. Fraction of Tax-Exempt Holdings is the percentage of marketable Treasuries held by potentially tax-exempt institutions.

| Variable | Expected Sign Model 1/Model 2 | Model 1 Total-month-end Idiosyncratic Pricing | Model 2 Idiosyncratic Pricing per Treasury |
|----------|-------------------------------|---------------------------------------------|------------------------------------------|
| Intercept | −3.3778                       | −1.75                                       | 0.178                                    |
| Post-Tax-Reform Dummy | −/−                        | −9.581                                     | −0.071                                   |
| Log Average Issue Size | −/−                         | −8.281                                     | −0.066                                   |
| Log Number of Issues | 7/−                      | 13.592                                     | 0.021                                    |
| On-Run-Premium | +/+                        | 18.528                                     | 0.105                                    |
| Fraction in Stripped Forms | −/−                    | −16.625                                     | −0.404                                   |
| Fraction of Tax-Exempt Holdings | −/−               | 8.998                                      | 0.071                                    |
| Adjusted R-squared | 0.22                      |                                             | 0.36                                     |
| No. of Obs. | 444                         |                                             | 444                                      |

27 We use the daily zero-coupon yield curves by Gurkaynak et al. (2007) to estimate the model implied yield of the on-the-run 10-year T-note. We have also used an alternative measure of the On-Run-Premium as the difference between the yields on the on-the-run issue and the first-off-the-run issue. The empirical results are qualitatively the same with the alternative measure.

28 We have also used the average Treasury bid/ask spreads as a measure of liquidity and the empirical result is similar. However, existing literature questions the validity and accuracy of the bid/ask spread reported in the CRSP Treasury database (Adrian et al., 2017; Duffee, 1996).
Fig. 6. Regression-predicted idiosyncratic pricing.
Panel A is a plot of regression predicted Total Month-end Idiosyncratic Pricing over the sample period, based on the regression Model 1 reported in Table 6. Panel B is a plot of regression predicted Idiosyncratic Pricing Per Treasury over the sample period, based on the regression Model 2 reported in Table 6.

Fig. 7. Frequency distribution of linear programming weights.
This figure plots the percentages the sample in each of 23 LP Weight buckets. The buckets range from $-1$ (Short Weight of 1) to 1 (Long Weight of 1) by an increment of 0.1 with negative (positive) values stand for Short (Long) Weights. Bucket 0 includes securities that are neither bought nor shorted in the LP model. Bucket $(-1, -0.9]$ contains securities with LP Short Weight greater than or equal to 0.9 but less than 1, etc.

4.2. Persistence in idiosyncratic pricing

Section 2.5 documents daily persistency in aggregate idiosyncratic pricing. This section investigates the month-to-month persistence in idiosyncratic pricing at the individual security level.

Following Ronn (1987), we define a security in a particular month as being High-Priced (Low-Priced) if it has a Short (Long) Weight greater than or equal to 0.8. A security is considered Fair-Priced in the month when it has Long and Short Weights less than 0.8, or effectively less than 0.2.

To examine month-to-month persistency in idiosyncratic pricing at the security level, we construct a month-to-month relative valuation transition matrix. This matrix tracks the numbers and percentages of securities that migrate from one state (High-Priced, Low-Priced or Fair-Priced) in one month to another state in the subsequent month. Table 7 reports the transition matrix. Approximately 86% of Fair-Priced securities remain in the Fair-Priced state and about 53% (56%) of Low-Priced (High-Priced) securities remain in the Low-Priced (High-Priced) category in the following month. Less than 7% (10%) of Low-Priced (High-Priced) securities migrate
Table 7
Relative valuation transition matrix.
This Table is the monthly transition matrix of the relative valuation of Treasury securities. Each Treasury security is classified into one of three states, depending on its LP Weights at the end of each month. Securities with Long (Short) Weights greater than or equal to 0.8 are classified as Low-priced (High-priced). Securities with LP weights, long and short, less than 0.8 are classified as Fair-priced. The number in each cell is the number of securities that migrate from one state in the current month (Rows) to another state in the following month (Columns). The percentage in the parenthesis in each cell is the percentage of securities in one state of the current month that migrates to another state in the following month. The diagonal elements of the matrix denote the numbers and percentages of securities remain in the same state at the following month.

| Current period | Next period |
|----------------|------------|
|                | Low-priced (Long Weight >= 0.8) | Fair-priced | High-priced (Short Weight >= 0.8) | Total |
| Low-priced (Long Weight >= 0.8) | 5510 (52.7%) | 4267 (40.86%) | 667 (6.39%) | 10,444 |
| Fair-priced | 3947 (7.09%) | 47,800 (85.8%) | 3927 (7.05%) | 55,674 |
| High-priced (Short Weight >= 0.8) | 987 (9.44%) | 3608 (34.5%) | 5862 (56.06%) | 10,457 |

Table 8
Security characteristics, types, and relative valuation.
The Table reports descriptive statistics of three subsamples of security-month observations based on monthly LP Weights. The High-priced (Low-priced) subsample includes securities with LP Short (Long) Weight greater than or equal to 0.8. The Fair-priced subsample include securities with LP weights, long and short, less than 0.8. Panel A reports the security characteristics (variable means) of the three subsamples. Age is the number of months since initial issuance. Log Issue Size is the natural logarithm of the amount of security issued (in millions of dollars of face value). Log Bid-Ask Spread is the natural logarithm of the difference in the quoted ask price and bid price (in cent) per $100 par. % in Stripped Form is the percentage of the amount outstanding of each security held in the form of Treasury Strips. Panel B reports the percentages of different types of Treasury securities in each subsample. On-the-run issues are the most recently issued security in its maturity category. Discount Bond is defined as securities with price less than par value. T-bond is securities with original maturity of or greater than 20 years. Ten-Year Note (Other Note) is Treasury note with original maturity equal to [less than] 10 years.

|          | High-priced (Short Weight >= 0.8) | Fair-priced | Low-priced (Long Weight >= 0.8) |
|----------|----------------------------------|-------------|---------------------------------|
| Panel A. Security characteristics | | | |
| Age (in months) | 53.12** | 51.58 | 79.46*** |
| Log Issue Size | 9.48 | 9.48 | 9.41*** |
| Log Bid-Ask Spread | 1.70*** | 1.78 | 1.61*** |
| Coupon Rate | 5.62*** | 6.56% | 7.28*** |
| % in Stripped Form | 1.11*** | 6.00% | 3.24*** |
| Panel B. Security types | | | |
| % On-the-run | 5.19*** | 2.73% | 2.60% |
| % Discount Bond | 29.90%*** | 23.38% | 15.34%*** |
| % T-bond | 16.33%*** | 25.98% | 26.45% |
| % Ten-Year Note | 28.88%*** | 15.35% | 18.04%*** |
| % Other Note | 54.49%*** | 58.66% | 55.50%*** |
| No. of Obs. | 10,619 | 56,680 | 10,619 |

* ** *** denote that the variable subsample mean is significantly different from that of the Fair-priced subsample at the 1%, 5% and 10% levels.

4.3. Security characteristics, types and LP weights

The persistence in idiosyncratic pricing at the individual security level further indicates that idiosyncratic pricing is not random but driven by some underlying persistent factors. This section investigates the characteristics of securities with idiosyncratic values to shed light on the determinants of relative valuations of Treasury securities.

Panel A of Table 8 reports the descriptive statistics of Treasury securities classified as High-priced, Fair-priced, and Low-priced. Age is the number of months since initial issuance. High-priced securities, with an average age of 53 months, are more recently issued than Low-priced securities. Log Issue Size is the natural logarithm of the amount of security issued (in millions of dollars of par value). The mean Log Issue Size of the Low-priced securities is significantly lower than their Fair-priced and High-priced counterparts. Log Bid-Ask Spread is the natural logarithm of the difference in the quoted ask price and bid price (in cent) per $100 par. Both the High-priced and Low-priced subsamples have significantly lower Log Bid-Ask Spread than the Fair-priced subsample. Interestingly, the three relative valuation subsamples have significantly different average coupon rates. The Low-priced (High-priced) subsample has significantly higher (lower) average coupon rates than the Fair-priced subsample. % in Stripped Form is the percentage of the amount outstanding of each Treasury security held in the form of Treasury Strips at the end of each month. Fair-priced securities have a significantly higher percentage held in stripped form than both the High-priced and Low-priced securities, suggesting Treasury stripping helps to reduce idiosyncratic pricing.

Panel B of the Table reports the percentages of different types of Treasury securities within the High-priced, Fair-priced, and Low-priced subsamples. More than 5% of High-priced securities are on-the-run issues, compared with about 2.73% (2.60%) for Fair-priced (Low-priced) securities. Discount bonds represent a significantly higher percentage (29.90%) of High-priced securities and significantly lower percentage (15.34%) of the Low-priced securities, consistent with the preferential tax treatment of discount bonds. T-

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29 We log-transform the bid-ask spread because the variable is highly skewed with large outliers. The un-transformed bid-ask spread has a skewness of 5.19 and a kurtosis of 44.10. In contrast, the skewness and kurtosis of the Log Bid-Ask Spread are 0.39 and 0.91, respectively.
30 Securities prior to the introduction of the Treasury STRIPS program or ineligible for the program have a value of 0 for this variable.
31 Note that Fair-priced securities account for almost three quarters of the sample. Thus, even though on-the-run issues represent a smaller percentage of Fair-priced securities, more than 60% of on-the-run issues are classified as Fair-priced.
bonds account for a significantly lower percentage (16.33%) of High-Priced securities versus the 25.96% of Fair-Priced securities. 10-year T-notes represent a significantly higher percentage (28.88%) of High-Priced securities. Notes other than 10-year notes are slightly more than half of each of the categories.

4.4. Determinants of relative valuation states

This section considers the relation between the characteristics of individual Treasury securities and idiosyncratic pricing with multinomial logistic (multi-logit) models. The explanatory variables include features of Treasury securities and dummy variables for different security types. Most explanatory variables are defined earlier. The On-the-run dummy is set to 1 for on-the-run issues and 0 otherwise. The Discount Bond Dummy is set to 1 for securities with original maturity greater than or equal to 20 years (less than 10 years). Ten-year notes serve as the base case. Relative Coupon Rate is the bond coupon rate divided by the average coupon rate of same-maturity bonds in the observation month.

Table 9 reports the results of the multi-logit models. Model 1 (2), with an indicator variable for High-Priced (Low-Priced) securities as the dependent variable and Fair-Priced securities as the reference group, compares the High-Priced (Low-Priced) securities with the Fair-Priced ones. Model 3 has Low-Priced securities as the reference group and an indicator variable for High-Priced securities as the dependent variable. It compares the High-Priced securities with the Low-Priced ones.

The findings from the multi-logit models in Table 9 are mostly consistent with the univariate analysis in Table 8. The coefficient on Age is significantly positive in both Models 1 and 2, suggesting that older securities are less likely to be Fair-Priced. Older securities are generally less liquid, making it harder for arbitrageurs to exploit any pricing inefficiency. The coefficient on Age is significantly negative in Model 3, implying that older bonds are more likely to be cheaper when not Fair-Priced. As Treasury securities age over time, increasing amounts are settled into investors’ portfolios and fewer are available for trading, making them less liquid and undesirable for investors.

The coefficients on Log of Issue Size are significantly negative in both the High-Priced/Fair-Priced and Low-Priced/Fair-Priced regressions, suggesting that Treasury securities with larger issue sizes are less likely to have idiosyncratic value. This finding is consistent with the time-series regressions in Table 6 which suggest increasing average issue sizes contribute to the secular decline in aggregate idiosyncratic pricing over the last four decades.

The coefficients on the Log Bid-Ask Spread are negative in both Models 1 and 2, suggesting that securities with large bid-ask spreads are less likely to be either High-Priced or Low-Priced. Bonds with large bid-ask spreads are generally less liquid and harder to trade, making them less desirable to investors. Consequently, it is not surprising that they are less likely to be High-Priced. However, it is counter-intuitive that they are less likely to be Low-Priced too. In addition, the marginally significant positive coefficient in Model 3 suggests that bonds with larger bid-ask spreads, when not Fair-Priced, are more likely to be High-Priced. We will revisit these counter-intuitive results in the next section.

The coefficients on the % in Stripped Form are significantly negative in both regressions, indicating that active Treasury stripping helps to ameliorate pricing efficiency.

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13 We do not use stated coupon rate because it is highly correlated with Log Issue Size ($\rho = -0.82$) due to the secular decline in Treasury coupon rates and increasing issue sizes over the last four decades.

14 In the time-series regressions in Section 3, we avoid market average bid-ask spread out of concern of noises and inaccuracy in the reported bid-ask spread. Without a good alternative at the security level, we include Log Bid-Ask Spread as an explanatory variable in the multi-logit models. Given the potential problems of the reported bid-ask spreads in the CRSP database as noted earlier, any empirical results on bid-ask spreads should be interpreted with caution.

15 Note that this variable is defined differently from the Fraction in Stripped Form in Section 3. % in Stripped Form is the percentage of each security held in stripped form.

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Electronic copy available at: https://ssrn.com/abstract=3441766
Interestingly, the coefficients on the On-the-Run dummy variable are significantly positive in both regressions, suggesting a higher likelihood of on-the-run issues being either High-Priced or Low-Priced.\(^\text{36}\) On the other hand, the significantly positive coefficient on the variable in Model 3 suggests that, when not Fair-Priced, on-the-run issues are more likely to be High-Priced than Low-Priced, consistent with empirical findings in the extant literature that on-the-run issues, on average, enjoy a price premium.

The coefficient on the Discount Bond dummy is significantly positive (negative) in the High-Priced/Fair-Priced (Low-Priced/Fair-Priced) regression, consistent with the preferential tax treatment of discount bonds prior the 1986 Tax Reform Act and the finding from the univariate analysis that discount bonds are more likely to be High-Priced and less likely to be Low-Priced. The 1986 Tax Reform Act eliminated the preferential tax treatment on all discount bonds purchased after April 1993.\(^\text{37}\) Thus, the effect of bond discount on idiosyncratic pricing is expected to concentrate in the period from 1980 to 1992 and disappear after 1993. A subsample analysis shows that the tax effect is indeed observable only during the 1980 to 1992 subsample period and discount bonds are no longer more likely to be High-Priced after 1993.\(^\text{38}\)

The coefficient on the T-Bond dummy variable is significantly negative in both regressions, indicating that T-bonds, relative to 10-year T-notes, are more likely to be Fair-Priced.\(^\text{39}\) On the other hand, the coefficients on the Other Notes Dummy are significantly negative in Model 1 but insignificant in Mode 2, implying that other Treasury notes are less likely to be High-Priced than 10-Year T-notes.

Finally, the coefficient on the Relative Coupon Rates is significantly negative (positive) in Model 1 (Model 2), consistent with the finding from the univariate analysis that higher coupon bonds are more likely (less likely) to be Low-Priced (High-Priced).\(^\text{40}\)

4.5. Bid-ask spread and relative valuation states

As the LP model assumes that an arbitrageur buys securities at the high ask prices and shorts at the low bid prices, it has the feature that, ceteris paribus, securities with large bid-asked spreads are more likely to be considered Fair-Priced, which might explain the counter-intuitive findings in the previous section. In order to remove the impact of bid-ask spreads on relative valuation, we repeat the analysis of the preceding section assuming securities are purchased or sold at the midpoint of the bid-ask prices. As detailed below, the results are essentially the same using the midpoints.

In Section 2.6, we showed that the aggregate and per-security idiosyncratic pricing based on the midpoint prices increases only slightly from the base case, indicating the bid-ask spreads do not have a large impact on overall idiosyncratic pricing.

To examine if bid-ask spreads significantly impact the portfolio weights of different securities, we calculate the correlation between the LP Weights (positive for non-zero Long weight and negative for non-zero Short Weight) from the base model and the model based on midpoint prices. The correlation coefficient is highly significant at 0.88. Furthermore, the High-Priced, Low-Priced and Fair-Priced indicator variables estimated from the two models have a correlation coefficient of 0.85.

Also, with the new relative valuation states based on the midpoint prices, we report the security characteristics of bonds of different valuation states and the results of the multi-logit model in the Modified Table 8 and Modified Table 9 in Appendix D. A comparison of the two tables in Appendix D and Tables 8 and 9 shows that the empirical results based on midpoint prices are essentially the same as those based on bid-ask prices. These findings suggest that the bid-ask spreads have a minimal influence on idiosyncratic pricing.

Finally, the coefficient on the Log Bid Ask Spreads is significantly negative in Model 2 of the Modified Table 9, similar to the results in Table 9. However, the coefficient turns to significantly negative in Model 3, indicating that bonds with larger bid-ask spreads, when not Fair-Priced, are more likely to be Low-Priced.

4.6. Summary

The empirical results from the analysis of idiosyncratic pricing are largely consistent with the findings from prior research and complement the findings from the time series analysis at the macro level. We document persistence in idiosyncratic pricing at the individual Treasury security level, supporting the daily persistence in aggregate idiosyncratic pricing. Consistent with findings of a large impact of the 1986 Tax Reform on aggregate idiosyncratic pricing, discount bonds are found to be more likely (less likely) High-Priced (Low-Priced). Further, at the micro level, we find Treasury stripping activities contribute to the reduction in idiosyncratic pricing.

5. Conclusion

Unique features and market frictions can lead to idiosyncratic value for some Treasury securities. Impediments to arbitrage prevent potential arbitrageurs from fully exploiting the idiosyncratic pricing.

A linear programming model is used to measure the idiosyncratic pricing of the marketable Treasury security market from 1980 to 2016. Over this entire time interval, T-notes and T-bonds have had an average idiosyncratic pricing of about $0.11 per $100 par value, more than 30% higher than the average bid-ask spreads. Empirical evidence suggests that the idiosyncratic pricing is driven by persistent factors and hard to be arbitraged away. Further, there has been a significant decline in idiosyncratic pricing over the last four decades. Average idiosyncratic pricing per Treasury security decreased from $0.25 in 1980–1984 to less than $0.05 after 2010.

This dramatic decrease in idiosyncratic pricing coincides with several institutional and market developments and tax changes that tend to reduce market frictions, increase market homogeneity, and lower costs to arbitrage. The empirical evidence suggests that the 1986 Tax Reform Act, Treasury strips, the larger issue sizes of Treasury securities, and increased market liquidity contribute significantly to the secular decline in idiosyncratic pricing. These findings demonstrate that the US Treasury market has become more homogeneous in pricing and is closer to the perfect market conditions as assumed by the LP model.
Appendix A. LP model: A hypothetical example

A hypothetical example is used in this Appendix to illustrate the LP model. Suppose there are six default-free bonds, named A to F, in a liquid market as shown in Table A.1. The maturities of the six bonds range from 3 to 7 periods, where each period is 3 months in length. The annual coupon rates vary from 4% to 8%. The bid and ask (settlement) prices are observed today. Half of the bonds are selling at a discount and the other half at a premium from the par values. The future cash flows, coupon payments, and principals are default-risk-free.

The LP model is used to identify a long-short portfolio that (1) maximizes the net cash flow today, (2) with the constraints that the net cumulative cash flows of all future periods are never negative. In addition, the LP model constrains the number of units of each bond to be bought or shorted to be no more than 1.

Table A.2 reports the solutions of the LP model for the hypothetical example. The second (third) columns are the LP Short Weight (Long Weight), or the number of units of each bond to be shorted (bought). The long-short portfolio contains two long positions: 0.56147 unit of bond C and 0.99711 unit of bond F, and four short positions in bonds A, B, D, and E. The Short Weights on the four bonds are 0.002834, 0.558636, 0.002779 and 1 unit, respectively.

The fourth column gives the cash inflows from the short proceeds (cash outflows of purchase costs) for bonds with non-zero Short Weight (Long Weight). Bonds are bought (shorted) at the ask (bid) prices. The total cash flows of the long-short portfolio are $0.033, which is called Total Month-end Idiosyncratic Pricing. The total portfolio cash flow in time period 1 is $0.283, which is carried over to time period 2 at a re-investment rate of 0%. The total portfolio cash flow in time period 2 is $-0.283. Thus, the net cumulative cash flow at time 2 is $0. The last two rows on the table report the portfolio total cash flows and net cumulative cash flows respectively at every future period. Given the LP constraints, the net cumulative cash flows are either $0 or positive from period 1 to 7.

Appendix B

This Appendix illustrates the differences and similarities between the Linear Programming (LP) Idiosyncratic Pricing and the Noise Measure of Hu et al. (2013) through a hypothetical numerical example.

Suppose there are seven risk-free bonds from A to G. As shown in the first two columns of Panel B of Table B.1, the maturities of the seven bonds range from 1 to 7 periods, or quarters, and annual coupon rates vary from 4% to 8%. Further, the seven bonds are priced based on the same underlying continuously compounded zero-coupon spot rates, $R_{0,n}$ (n = 1 to 7), reported in the first row of Panel A of Table B.1. The prices, yields to maturity (YTM) and Macaulay durations of the seven bonds are contained in Panel B.44

The first case (base case) calculates the LP Idiosyncratic Pricing and the HPW Noise Measure when all bonds are priced perfectly by the assumed term structure. In the second case, we assume a slight steepening of the yield curve. In the other four cases, prices of some bonds deviate from the assumed term structure. The LP Idiosyncratic Pricing and the HPW Noise Measure are calculated in each of the six cases.

Case I

Case I is the base case in which the seven bonds are priced by the same underlying zero-coupon spot rates. Not surprisingly, the

44 The underlying zero-coupon spot rates can be backed out from the bond prices.
Table B.1
Base case.
This Table gives information of a hypothetical example that compares the LP Idiosyncratic Pricing with the Noise measure of Hu et al. (2013). Seven different bonds, from A to G, have maturities ranging from 1 to 7 periods. Each period is 3 months in length. Panel A reports the underlying zero-coupon spot rates used to price the seven bonds and model fitted spot rates by the methodology of Hu et al. (2013). Panel B reports the terms, prices, yields to maturity (YTM) and durations of the seven bonds. In addition, Panel B also reports the model-fitted prices and model-fitted YTMs by the methodology of Hu et al. (2013). The last column of Panel B contains the deviation of the model-fitted YTM from the actual YTM.

| Panel A | Term structure |
|---------|----------------|
| Time periods | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Underlying Spot Rates ($R_{0,n}$) | 1.000% | 1.350% | 1.550% | 1.700% | 1.800% | 1.900% | 1.950% |
| Model-fitted Spot Rates ($R_{f,n}$) | 1.000% | 1.345% | 1.549% | 1.701% | 1.816% | 1.898% | 1.950% |

| Panel B | |
|---------|----------------|
| Bonds | Maturity (in period) | Coupon Rate | Price | YTM | Duration (in years) | Fitted Price | Fitted YTM | Yield Deviation |
| A | 1 | 4.00% | $100.985 | 4.020% | 0.250 | $100.985 | 4.020% | 0.000% |
| B | 3 | 5.00% | $100.318 | 6.278% | 0.738 | $100.321 | 6.274% | 0.004% |
| C | 4 | 6.00% | $99.149 | 6.895% | 0.985 | $99.145 | 6.900% | –0.004% |
| D | 4 | 5.00% | $98.195 | 6.899% | 0.988 | $98.191 | 6.903% | –0.004% |
| E | 6 | 8.00% | $100.425 | 7.694% | 1.443 | $100.439 | 7.685% | 0.010% |
| F | 7 | 7.00% | $100.299 | 7.893% | 1.650 | $100.295 | 7.896% | –0.003% |
| G | 7 | 7.60% | $101.418 | 7.889% | 1.643 | $101.414 | 7.891% | –0.003% |

Table B.2
Comparisons of LP Idiosyncratic Pricing and HPW Noise.
This Table compares the LP Idiosyncratic Pricing with the Noise measure of Hu et al. (2013) in seven different scenarios of the hypothetical example. Each row represents one particular scenario. Column 2 describes the different scenarios in spot rates and Column 3 reports the bond prices under each scenario. Column 4 reports the changes in bond prices from the base case. Spot rates and prices of bonds not reported remain the same as the base case. The last two columns give the LP Idiosyncratic Pricing and the HPW Noise measures respectively.

| Case | Scenario | New Prices | Price Changes | LP Idio. Pricing (in dollar) | HPW Noise (in basis points) |
|------|----------|------------|---------------|-------------------------------|-----------------------------|
| I    | Base Case | P$y$ = 99.983 | ΔP$y$ = –0.316 | $0.000 | 0.489 |
| II   | $R_{0,7}$ = 2.00% for all bonds | P$y$ = 101.102 | ΔP$y$ = –0.443 | $0.000 | 1.082 |
| III  | $R_{0,7}$ = 1.71% for C and $R_{0,7}$ = 1.70% for all others | P$y$ = 99.110 | ΔP$y$ = –0.039 | $0.029 | 1.093 |
| IV   | $R_{0,7}$ = 1.96% for F and $R_{0,7}$ = 1.95% for all others | P$y$ = 100.236 | ΔP$y$ = –0.063 | $0.057 | 1.077 |
| V    | $R_{0,7}$ = 1.80% for C and $R_{0,7}$ = 1.70% for all others | P$y$ = 98.765 | ΔP$y$ = –0.384 | $0.373 | 11.885 |
| VI   | $R_{0,7}$ = 2.05% for F and $R_{0,7}$ = 1.95% for all others | P$y$ = 99.669 | ΔP$y$ = –0.630 | $0.624 | 10.657 |

LP model finds a potential arbitrage profit of zero, i.e. no idiosyncratic value.\(^{42}\)

Next, following the methodology of Hu et al. (2013), we first compute the Nelson-Siegel-Svensson model fitted spot rates by minimizing duration-adjusted price deviations. The second row of Panel A of Table B.1 reports the model fitted spot rates ($R_{0,n}$). The actual and fitted spot rates are quite close with deviations ranging from 0 to 1.6 basis points. With the fitted spot rates, we calculate the model fitted bond prices, the fitted YTM and deviations from actual YTM. These are reported in the last three columns of Panel B of Table B.1. A comparison of the last three columns of Table B.1. A comparison of the actual YTMs (YTM) and the model-fitted YTMs (model-fitted YTM) suggests a good fit with price (YTM) deviations ranging from $0$ to $0.014$ (0 to 1 basis point).

Finally, we calculate the HPW Noise Measure and report it in the first row and last column of Table B.2. While the seven bonds are priced perfectly by the same underlying spot rate curve without any idiosyncratic values, the HPW Noise Measure has a positive value 0.489 basis points. The HPW Noise finds idiosyncratic pricing when there is none. In contrast, the LP Idiosyncratic Pricing correctly identifies no idiosyncratic values.

Case II

In Case II, we slightly steepen the underlying yield curve at period 7 by increasing $R_{0,7}$ by 5 basis points to 2%. The increase in $R_{0,7}$ reduces the prices of bonds F and G, but has no impact on other bonds. The new prices and price changes are reported in the third and fourth columns of Table B.2 respectively. Given the same impact on bonds F and G, the change in $R_{0,7}$ does not introduce idiosyncratic pricing. Then we re-run the LP model and re-fit the yield curve to get the two measures of idiosyncratic pricing. The LP Idiosyncratic Pricing remains at zero. On the other hand, the Noise Measure increases to 1.082 basis points.

Cases I and II suggest that the HPW Noise Measure is a noisy proxy of idiosyncratic pricing in that (a) it can be non-zero in the absence of any idiosyncratic pricing, and (b) it is affected by the shape of the yield curve.\(^{33}\)

Cases III and IV

In cases III and IV, we introduce idiosyncratic pricing. In each case, we assume that one of the spot rates changes for a specific bond by one basis point while the spot rate remains unchanged for all other bonds. This procedure introduces a small idiosyncratic decline in price for one bond.

In case III, the price of bond C drops by 3.9 cents to $99.11 while all other prices remain unchanged. The idiosyncratic price decline is caused by assuming $R_{0,4}$ of 1.71% for bond C while it remains at 1.70% for all other bonds. The LP model identifies an Idiosyncratic Pricing of 2.9 cents and the HPW Noise measure is 1.093 basis points.

\(^{42}\) In this example, we assume that securities can be bought and shorted at the same price, i.e., there is no bid-ask spread. We make this assumption to be consistent with the HPW Noise measure where average bid-ask price is used.

\(^{33}\) We identify other factors, such as the number of bonds, which affect the HPW Noise in the absence of idiosyncratic pricing.
In case IV, the price of bond F drops by 6.3 cents while the prices of the other bonds remain unchanged. The idiosyncratic price decline is caused by assuming $R_{2.7}$ of 1.96% for bond F while keeping the rate at 1.95% for all other bonds. After rerunning the LP and curve-fitting models, we find an LP Idiosyncratic Pricing of 5.7 cents and Noise Measure of 1.077 basis points.

In both cases, the LP and curve-fitting models respond to the introduction of idiosyncratic pricing caused by a one basis point change in one of the spot interest rates. The LP Idiosyncratic Price increases fairly close to the actual dollar idiosyncratic pricing. The Noise Measure increases significantly from the base case and is close to the actual yield deviation of 1 basis point.

Cases III and IV show that both measures work very well for their intended purposes: measuring idiosyncratic pricing in terms of dollars (LP Idiosyncratic Precisions) and in terms of yield deviations (Noise Measure). The Noise Measure focuses on yield differences while the LP approach captures the price impact of yield differences for individual maturities. The LP approach captures the different effect on idiosyncratic pricing by the location of yield deviations along the yield curve, while the HPW Noise treats yield deviations at different points of yield curve equally.

Cases V and VI

Cases V and VI are very similar to cases III and IV except we assume a 10-basis-point idiosyncratic deviation in $R_{0.4}$ and $R_{0.7}$ for bonds C and F respectively. The prices of bonds C and F decrease by 38.4 cents and 63 cents respectively. Correspondingly, the LP model identifies an Idiosyncratic Pricing of 37.3 cents and 62.4 cents respectively, very close to the actual idiosyncratic pricing. The Noise measures are 11.886 and 10.657 basis points, also close to the assumed 10-basis-point deviations in $R_{0.4}$ and $R_{0.7}$. These two cases further demonstrate that both measures of idiosyncratic pricing perform well for their intended purposes. As a result, these two measures are positively correlated.

While similar, these two measures are designed for different purposes and each fit better for its intended goal. The HPW Noise measure is designed to proxy for aggregate market liquidity and illiquidity premiums which are traditionally measured in yields. On the other hand, the LP Idiosyncratic Pricing is designed to measure the magnitude of the potential and theoretical arbitrage profits exploitable in a frictionless market without limitation to arbitrage. An idiosyncratic pricing of $2 on a 10-year bond represents a much larger theoretical arbitrage profits than a $0.5 idiosyncratic pricing on a one-year note, even though their yield deviations might be similar.

Appendix C. Limits to arbitrage and unique features

This appendix contains a brief summary of some of the published papers discussing limits to arbitrage and unique features of bonds.

A.1. Impediments to arbitrage

In a perfect and homogenous market without arbitrage restrictions or costs, any idiosyncratic pricing should be arbitraged away. In actual practice, there are significant impediments or costs to risk-free arbitrage.

A good example of the limiting effects of costs to arbitrage is the repo specialness of the on-the-run issues (Duffie, 1996; Krishnamurthy, 2002). To profit from the price difference between a high-pried on-the-run issue and an otherwise similar but low-priced off-the-run issue, an investor would short the on-the-run issue and long the off-the-run issue. To establish the short position, the investor engages in a reverse repo in the on-the-run issue, earning the lower special repo rate from the on-the-run issue. In the meantime, the investor finances the long position by a repo agreement in the off-the-run issue, paying the higher general collateral repo rate. The cost of this strategy is the difference between the (lower) special repo rate on the on-the-run issue and the (higher) general collateral repo rate. This difference prevents arbitrage from eliminating the price premium for on-the-run issues.

Other direct costs to arbitrage include transaction costs, bid-ask spreads, and haircut costs in the repo market. Availability of equity capital for arbitrage positions and leverage constraints on arbitrageurs pose further impediments to arbitrage (Shleifer and Vishny, 1997; Gromb and Vayanos, 2010). Through a theoretical model, Liu and Longstaff (2004) demonstrate that collateral requirements on short positions can make some ‘textbook’ arbitrage strategies infeasible or money-losing.

B.1. The relative pricing of US Treasury securities

B.1.1. Asymmetric tax treatments for discount and premium bonds

Prior to the 1986 Tax Reform Act, discounts on market discount bonds were treated as capital gains at the maturity or disposal of the bonds. This created two tax advantages for discount T-notes and T-bonds. First, the market discount was taxed at the lower capital gain tax rate. Second, the tax on the discount was deferred until the disposal or maturity of the bond. Numerous studies have documented the impact of the asymmetrical tax treatment on US Treasury pricing and clientele effects (Schaefer 1981, 1982; Jordan, 1984; Litzenberger and Rolfo, 1984; Ronn, 1987, and Kamara, 1994).

B.1.2. On-the-run effect

A well-documented idiosyncratic pricing in the Treasury market is the on-the-run effect. Warga (1992) finds that returns of on-the-run Treasuries, or the most recently issued Treasury securities, average 55 basis points lower than otherwise similar off-the-run Treasuries, suggesting overpricing of the on-the-run issues. Goldreich et al. (2005) find evidence that the liquidity of on-the-run issues is priced. The extant literature offers three explanations for the on-the-run effect. First, on-the-run issues command a higher price because of higher liquidity (Sundaresan, 2002; Fleming, 2002). Second, on-the-run issues are special in the repo market, i.e., the repo rates of the on-the-run issues are significantly lower than the general collateral repo rates (Duffie, 1996). Third, Vayanos and Weil (2008) proposes a search-externality explanation for the on-the-run effect.

B.1.3. Liquidity effect

In addition to the liquidity difference between the on-the-run and off-the-run issues, there is also a significant variation in liquidity among the off-the-run issues. Amihud and Mendelson (1991) compare T-bills and one-year T-notes with six months left to maturity. They find that T-notes have wider bid-ask spreads, suggesting lower liquidity for T-notes. Further, T-notes have significantly higher yields than T-bills, indicating an illiquidity premium on T-notes. In the same vein, Musto et al. (2018) find that bid-ask spreads on T-bonds are twice those on 10-year T-notes, and the yields on T-bonds are higher than T-notes with similar time left to final maturity. Longstaff (2004) indicates that the flight-to-liquidity can have an important impact upon the pricing of US Treasury bonds during crises.
B.1.4. Aging effect

Closely related to the liquidity effect is the aging effect of US Treasury securities, documented by Fontaine and Garcia (2012) and Diaz and Escribano (2017). As Treasury securities age over time, a larger and larger fraction may be acquired by long-term buy-and-hold investors, leading to lower liquidity. Diaz and Escribano (2017) find higher yields on older T-notes, indicating an illiquidity premium.

B.1.5. Issue size effect

Treasury security issue size could potentially affect bond yields in two opposite directions, as discussed by Fleming (2002). On the one hand, large issue size may push down prices and result in higher yields due to demand and supply imbalance. On the other hand, if larger issue size leads to higher liquidity, investors would be willing to accept a lower yield. Fleming (2002) finds evidence that increased issue size of reopened 52-week T-bills leads to both higher liquidity and lower yields than comparable maturity T-bills.

B.1.6. Deliverability effect

Several studies have shown that Treasury securities eligible for delivery into futures contracts have higher prices than otherwise similar non-deliverable securities. Garbade (1985) and Simpson and Ireland (1985) document small but statistically significant price premiums on deliverable Treasury bills. Kuipers (2008) has similar findings on deliverable 30-year T-bonds. Furthermore, Sack (2000) finds that the cheapest-to-deliver Treasury securities have significantly lower yields than the implied yields based on coupon Treasury strips.

Appendix D

Tables D.8 and D.9

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**Modified Table D.8**

Based on midpoint Bid-Ask prices.

| Panel A. Security characteristics | High-Priced (Short Weight >= 0.8) | Fair-Priced | Low-Priced (Long Weight >= 0.8) |
|-----------------------------------|-----------------------------------|-------------|---------------------------------|
| Age (in months)                   | 52.40***                         | 51.29       | 74.91***                        |
| Log Issue Size                    | 9.51***                          | 9.47        | 9.44***                         |
| Log Bid-Ask Spread               | 1.65***                          | 1.81        | 1.62***                         |
| Coupon Stripped Form             | 5.54***                          | 6.64%       | 7.08%**                         |
| % in Stripped Form               | 1.08%**                          | 6.56%       | 2.81%**                         |

| Panel B. Security Types          |                                    |             |                                 |
|----------------------------------|-----------------------------------|-------------|---------------------------------|
| % On-the-run                     | 4.58%***                         | 2.83%       | 2.34%**                         |
| % Discount Bond                  | 29.21%***                        | 23.67%      | 15.28%**                        |
| % T-bond                         | 15.21%***                        | 27.83%      | 22.84%**                        |
| % Ten-Year Note                  | 25.54%***                        | 15.16%      | 18.65%**                        |
| % Other Note                     | 59.24%***                        | 57.01%      | 58.51%**                        |
| No. of Obs.                      | 13,600                           | 50,867      | 13,531                          |

**Modified Table D.9**

Based on midpoint Bid-Ask prices.

| Model 1 High-Priced/Fair-Priced  | Model 2 Low-Priced/Fair-Priced   | Model 3 High-Priced/Low-Priced |
|----------------------------------|----------------------------------|--------------------------------|
| Intercept                        | 2.074 (0.00)                     | −0.906 (0.00)                   | 2.981 (0.00)                     |
| Age (in months)                  | 0.007 (0.00)                     | 0.009 (0.00)                    | −0.002 (0.00)                    |
| Log Issue Size                   | −0.184 (0.00)                    | −0.137 (0.00)                   | −0.048 (0.04)                    |
| Log Bid-Ask Spread               | −0.412 (0.00)                    | −0.280 (0.00)                   | −0.132 (0.00)                    |
| % in Stripped Form               | −7.084 (0.00)                    | −3.284 (0.00)                   | −3.800 (0.00)                    |
| On-the-run Dummy                 | 0.566 (0.00)                     | 0.273 (0.00)                    | 0.293 (0.00)                     |
| Discount Bond Dummy              | 0.226 (0.00)                     | −0.156 (0.01)                   | 0.382 (0.00)                     |
| T-bond Dummy                     | −0.954 (0.00)                    | −0.798 (0.00)                   | −0.156 (0.00)                    |
| Other Note Dummy                 | −0.450 (0.00)                    | 0.067 (0.02)                    | −0.517 (0.00)                    |
| Relative Coupon Rate             | −0.755 (0.00)                    | 1.068 (0.00)                    | −1.824 (0.00)                    |
| No. of Obs.                      | 77,917                           |                             |                                 |
| Pseudo R-squared                 | 0.11                             |                             |                                 |

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