Time Variation in Rates of Depreciation and Price Change for Personal Computers

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Abstract

We use a consistently-constructed dataset of used personal computer prices spanning nearly the entire history of the industry to simultaneously identify the rate of depreciation for the installed base of computers and the constant-quality price trend for new PCs. This allows us to examine the joint movement of these series over time. We find that faster quality-adjusted price declines of PCs in periods around recessions are accompanied by lower depreciation rates and that the slower price declines since the mid-2000s have been acompanied by lower rates of depreciation. This provides evidence that the assumption of time-invariant depreciation rates in the national accounts may bias the dynamics of capital stocks and multifactor productivity. We also observe the entry and rapid market penetration of desktop, laptop and tablet computers, and study the role of platform maturity and entry of competing platforms on depreciation. Finally, the paper provides an alternative to official sources of information about recent trends for computer prices at a time when the issue is of some importance.

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1 Introduction

This paper considers the question of how depreciation rates for computers have varied over time and across platforms. We extend the existing data on used desktop personal computer (PCs) prices for 1985-2002 employed in Doms, Dunn, Oliner, and Sichel (2004), hereafter referred to as DDOS (2004), through 2014, and we expand the data to include laptop and tablet PCs. Our consistently constructed dataset over a long time-span allows us to explore whether depreciation rates have slowed since the earlier analysis, and the effect on depreciation rates of emerging platforms, the business cycle, and an apparent marked slowdown in price trends in the market. In addition, a byproduct of our analysis is an estimate of the devaluation effect on used equipment corresponding to price trends in the new PC market, thus providing complementary results to official statistics on PC price trends, which have been under scrutiny recently.

Information technology, which accounts for roughly thirty percent of U.S. fixed asset investment, has historically been characterized by extremely rapid technical change, leading the capital stock to quickly grow obsolete. However, this rapid advance in the performance of new capital vintages is a regularity, not a law. The rate of change is determined in part by the underlying pace of scientific innovation. For example, Jorgenson (2001) noted that the frontier of electronic miniaturization accelerated in the early 1990s, and Pillai (2013) observed it later slowed in the early 2000s. And, the rate of change in performance is affected by the structure of the market for IT capital. For example, the appearance of PC 'clones' in the late 1980s, and of mail-order vendors in the 1990s boosted competition and led manufacturers to roll out new features more quickly. Consequently, the pace of obsolescence may vary over time and depreciation rates may not be constant.

Furthermore, the state of business demand varies over time as a function of the business cycle. Firms may hold off on capital deepening when their future is more uncertain and labor is abundant and inexpensive. Thus, for both supply side and demand side reasons, the depreciation rate may fluctuate over time. And yet, for the standard sources (such as the BEA/BLS Industry-Level Production Accounts), the depreciation rate for computers is assumed to be constant. If incorrect, this assumption would lead capital stock measures, the flow of capital services, and the decomposition of output and productivity to be inaccurate. This is a particularly important issue in recent years when the pace of price decline for computers has slowed dramatically.[1]

[1]The accuracy of this measured slowdown is subject to debate. See Byrne and Pinto (2015) for

Because depreciation rates employed remain aggressive, as estimated using data from the 1990s, the capital stock has dwindled.

This analysis is warranted for another reason as well. The U.S. business PC market has changed since the 1990s IT boom. Laptops accounted for 61 percent of unit sales in 2015, up from 24 percent in 2000, according to IDC, Inc. In addition, the emergence of tablet PCs (and smartphones) and a shift toward purchased IT services (e.g. from cloud datacenters) is pulling IT investment away from traditional desktops as well (Byrne and Corrado, 2016). Replacement cycles have reportedly lengthened for desktop PCs, suggesting they may depreciate more slowly (ComputerWeekly, 2016). This raises the question of whether depreciation studies conducted with data on desktops alone are sufficient for more recent years.

This paper sheds light on these questions with a thirty-year data set on used computer prices and computer characteristics, an extension of the data on desktop computers used in DDOS (2004), which went through 2002, and expanded to include data on laptops and tablets. The covariation of used prices with computer age, vintage, and features allows us to identify constant-quality depreciation rates for these three platform types as they vary over time.

A useful by-product of the study is a set of constant-quality price indexes for new desktops, laptops, and tablets. This provides an opportunity to corroborate BEA investment prices over a period for which there is little outside research and has the appeal of a consistent set of data over a long period of time.[2]

2 Description of the Data

We build upon a dataset originally constructed in DDOS (2004). The data used in that paper were drawn from computer 'bluebooks' published by Orion Research between 1985 and 2002, and consisted of used desktop PCs for Compaq, Dell, IBM, and Packard Bell. These catalogs contain prices for various types of used computer equipment and peripherals. For each item, the bluebook entry lists information on the manufacturer, the model name and number, the year or years in which the model

further discussion.

[2]Byrne, Oliner, and Sichel (2015) and Aizcorbe and Pho (2005) use scanner data for new PC prices spanning 2007-2015 and 2001-2004 respectively. Berndt and Rappaport's (2003) wide-ranging study begins in 1976 but stops in 2002.

was sold new by the manufacturer, and the current used price for the product.[3] Each computer bluebook entry also includes a brief description with details on the model's technical characteristics, most notably, the family and speed of the central processing unit (CPU), the amount of random access memory, and the capacity of the hard disk drive.[4] According to the publisher, the data for these early bluebooks were collected mainly using surveys of used equipment dealers, most commonly pawn shops.

We extend the sample of used PCs in DDOS (2004) to include two additional platforms (laptops and tablets) and a few more brands of PCs (e.g., Apple and HP), and to cover a longer period from 1985 to 2014.[5] To extend the time period of the sample, we first obtained bluebooks published from 2004 to 2006 from used book sellers and the Library of Congress. Data from these editions were in hard copy format, and thus given time constraints, we digitized the entries for at least the five brands with the highest average U.S. market share in the five years preceding each edition. For observations from 2007 to 2014, we purchased two snapshots per year of model information and used pricing from online data vendor usedprice.com, which had acquired the rights to publish the Orion bluebook data. The format of the electronic data from usedprice.com was consistent with the earlier bluebooks, and we again obtained data for the top five brands in each category of PC (desktop, laptop, tablet). Our dataset includes all companies that accounted for 5 percent or more of the market in at least one year in the 1990s, and for 2 percent or more for at least one year more recently.[6] These more recent vintages of bluebooks exploit the abundance of price quotes found on the Internet (including from pawn shops), but we believe reflect the same market as earlier vintages. We also extend the sample before 2003 to include laptops and additional

[3]The bluebooks actually include four prices for each listed PC: the "new list" price, which is the original manufacturers' suggested retail price (MSRP) associated with a model in the year it is first introduced, the retail "current used" price, and the wholesale prices for units in "mint" condition and "average" condition. We focus on the "current used" price for our empirical work, which represents the average retail price at which the publisher believes the computer could be sold in 30 days or less. We think the new list price, or MSRP, is of less value for the analysis because it excludes discounts offered by computer manufacturers and thus may not represent the actual transaction price. The wholesale mint and average condition prices are more speculative and we do not draw inferences from them.

[4]In many cases, several additional characteristics were also listed, including whether the PC has a monitor, a CD ROM drive, a DVD player, a fax/modem, a video card, a sound card, or a network card. However, the reporting of these features is incomplete across models and across years.

[5]We define laptops broadly to include all portable PCs that fold closed and do not function without their keyboard. Tablets have a slate design exclusively or can be converted to a fully functional slate form.

[6]For the 2007-2014 period, the top five vendors accounted for over 80 percent of U.S. PC sales for each of the categories.

brands of desktops.

A key variable that determines how much an asset has depreciated is its age, or how far along it is in its service life. As in the previous analysis, we define "model age" as the estimated amount of time that has elapsed since the first shipment of a given model. For example, the Dell "Dimension 8100" with a Pentium IV processor was first sold in 2001, while an earlier model, the "Dimension V350" with a Pentium II processor, was first sold in 1998. When measured in terms of model age, the V350 units are three years older than the 8100 units. The older model would be expected to sell at a lower price both because it is a less powerful computer than those at the frontier and because it likely has fewer remaining years of use before obsolescence causes retirement to occur.[7]

Because high-tech goods depreciate quickly, we also attempt to be as precise as possible about the timing of the observed prices. Table 1 lists each edition of the bluebooks included in our sample along with the reference time period in which we assume the prices were observed. As shown in the final column of the table, we construct the time and age variables at the monthly frequency using the midpoint of the date range for the given survey period. For example, we assign the price observations from the 2001 bluebook to November of the prior year. To calculate model age from a bluebook published annually, we assume that a given model was first shipped in June of the year it was introduced, which we label its "model year". Model age is then defined as the number of months between the assumed first-shipment date and the survey date. For instance, the 2001 bluebook price for a PC listed as first sold in 1998 would be associated with a model age of 29 months (June 1998 to November 2000). Beginning in 2007, we have two sets of price observations per year for desktops and laptops, and monthly price observations for tablets.

Figure 1, shows the histograms and distributions by time period, model age, and brand for desktops, after having dropped outliers and observations with incomplete data from the sample. For desktops, our dataset spans 30 years, covering all but the earliest years of the history of the market for PCs. Although, the sample size in considerably smaller in the 1980s and early 1990s, we are currently working on extending the DDOS (2004) sample to include more brands and PCs, especially in those years, and so far we have been able to do that for 2001 and 2002. It is interesting to note that both the age and brand distributions of desktops can change noticeably

[7]To the extent that elapsed time of actual use causes depreciation through 'wear and tear' on the equipment, our measure of age will not be appropriate. We believe this is a second-order concern.

over time. In particular, the age distribution is tilted towards younger PCs in the 1980s and early 1990s and towards older PCs after the early 2000s. Controlling for these trends, there seems to occur a slight shift of the age distribution towards older computers following recessions. On the brand distribution, we can see the entry and exit of a few brands, such as IBM and Lenovo.[8]

As shown in Figure 2, our sample for laptops currently begins in 2001, and we are currently processing data that may span back to the early mid 1990s. We find broadly similar patterns to desktops for the age and brand distribution of laptops. Finally, Figure 3 shows that our tablets sample extends to the earliest years of significant sales. Likely reflecting the nascent nature of this platform, the age distribution is still heavily tilted towards younger tablet PCs.

The nearly monotonic increase in price observations by year partly reflects some tendency for the publisher to retain models found in previous years in the catalog. In fact, the raw age distribution of used PCs (not shown) has a considerable mass of very old PCs, but in cleaning the data we decided to drop PCs that are 9 or more years old (see below). Although not shown, the variation of price observations within years, brands, and model ages is also significant. One thing worth noting is that the frequencies correspond to price listings, not transaction quantities in the market for used computers. Although we do not observe quantities sold, they are arguably not necessary for the hedonic approach to estimating constant-quality prices that we use in this analysis because the PC market is sufficiently competitive, though we return to this assumption later.

In the hedonic regressions that follow, we attempt to control for differences in product quality using several approaches. First, we include information on the key quantifiable characteristics of each PC, namely, the speed of its central processing unit (MHZ) in MHz, the amount of random access memory (RAM) in MB, and the amout of hard disk storage (HD) in GB. We also construct an identifier for models that are near the frontier of technologies available at the time a price was observed. Previous work by Dulberger (1989), Oliner (1993), and DDOS (2004) has shown that, controlling for other performance characteristics, the prices of semiconductors, mainframes, and PCs can vary significantly depending on whether they are near the technological frontier, a result that was interpreted as evidence of disequilibrium in these markets.

Table 2 reports various summary statistics for various characteristics by year of

[8]We are currently trying to extend further back in history PCs for Apple, HP and Dell (under their initial Limited PCs brand).

sales. The final filtered samples contain more than 35,000 observations for desktops, 30,000 observations for laptops, and almost 4,000 observations for tablets. For all platforms, the sample size is signifcantly higher in latter years than in the earlier years.

Figures 4 and 5 show the evolution of the key characterics for the average used desktop and laptop PC, respectively. In these figures, we control for the brand and the age of each PC in an attempt to account for the changes in the age and brand distribution of our sample over time that we showed earlier. The top charts show the average for each used price reference period in our sample, while the bottom charts provide a better way to control for age by showing the average by year of introduction of the PC. For desktops, we emphasize both the acceleration in the pace of increase of the key MHZ, RAM, and HD characteristics around the mid-1990s, followed by a slowdown after the mid-2000s. Overall, these two patterns are a bit less apparent for laptop PCs, in part because the sample for laptops starts only in 2001.

As shown previously in Byrne et al. (2015), the CPU speed flattens out after the mid-2000s, and stops rising as fast as RAM and HD. This relative underperformace of MHZ seems to have started a bit earlier for laptops. This suggests that other characteristics of the CPU may have become increasingly important for its overall performance (e.g., the number of cores) since the mid-2000s. Accordingly, we also include a performance index for the CPU in each PC as an additional check for the adequacy of MHZ over this period, following the evidence that these scores matter for PC hedonics (Byrne et al., 2015). As shown in figures 4 and 5, these performance scores of the CPU continue to rise at about the same pace as RAM and HD after the mid-2000s, even if they may also show some slowing in the pace of increase more recently.

Finally, we also attempt to include other characteristics of PCs, such as whether they include a monitor and its size, and whether they include a CD ROM or DVD.

3 Econometric Analysis of Used PC Prices

In this section we obtain estimates for the three main determinants of used prices of PCs: quality change, constant-quality price change, and economic depreciation. Following DDOS (2004), we use the following specification to decompose used computer

prices:

$$\ln(p) = \alpha + \beta_1 \ln(MHZ) + \beta_2 \ln(RAM) + \beta_3 \ln(HD) + \gamma t + \phi a + \boldsymbol{\eta X} + \epsilon \qquad (1)$$

where p is the price of the used computer, $\ln(MHZ)$ is the log of CPU speed, $\ln(RAM)$ is the log of random access memory, $\ln(HD)$ is the log of hard disk size, a is the age of the computer, and $\boldsymbol{X}$ is a vector of additional control variabless. These controls include the brand of computer, other characteristics of the PC (e.g., whether it includes a CD ROM/DVD, a monitor and its size), and a benchmark performance measure for each computer's processor chip. In the simplest specification, we obtain the average rates of constant-quality price change and depreciation for the entire period under analysis, but we also use specifications with richer dynamics along both time and age dimensions. For tablets, because we can observe the evolution of prices for specific computer models repeatedly over time, we also estimate fixed-effects regressions.

We impose a variety of selection criteria for the observations included in the regressions. In particular, we exclude observations that are missing data on price, age, or the four main characteristics, i.e., the speed of the CPU (MHZ), the amount of random access memory (RAM), the size of the hard disk (HD), and the type of CPU. We also exclude observations for PCs for which the used retail prices, relative to the price as new, were in the top 1 percent or the bottom 5 percent of the price distribution for the given PC type (i.e. desktop, laptop, tablet), brand and age, which removed from the sample what appear to be collectors' items and items that were most likely being sold for scrap.[9] We also exclude from the sample models aged 9 years or more, because beyond this point computers appear to be essentially of no value—their price does not change—other than for scrappage or collecting. Finally, we exclude the top and bottom 1 percent of observations for MHZ, RAM, and HD for the given PC type and year of introduction, and all servers and PCs with more than one hard drive.

3.1 Desktop PCs

Table 3 presents the regression results for desktop PCs using a variety of alternative specifications and sample periods, and tables 6 and 7, respectively, report the annualized depreciation and changes in constant-quality prices implied by the regressions. In each regression, $\boldsymbol{X}$ includes dummy variables for each brand of computer (not shown).

[9] There is a market for PCs too old to be functionally useful because of their precious metal content.

We also tried including an indicator variable for leading edge computer models based on a simple average of standardized measures of MHZ, RAM, and HD by brand and by year of introduction, defined as deviations from the mean over the standard deviation. Within each brand and vintage, we then ranked all computers according to this index and constructed a dummy variable that equals one for computers in the top 10th percentile of the distribution. The coefficients on this indicator variable were not generally statistically significant and did not enter with the expected (positive) sign; consequently, we did not include this dummy variable in $\boldsymbol{X}$ for the specifications shown here.[10]

Column (1) of table 3 shows results of a regression where the time period of the sample is restricted to be the same as in DDOS (2004). The results here for depreciation are qualitatively similar to those in the previous analysis; in particular, the implied depreciation rate of desktop PCs (unadjusted for the selective nature of retirements) is 12.6 percent per year, only a little faster than the DDOS (2004) estimate of 9 percent (averaged over the first five year's of the model life cycle).[11] Over the same time period, however, the regression results imply that constant-quality prices for used desktops declined by an estimated annual rate of 39.5 percent, nearly 7 percentage points faster than in the baseline specification in DDOS (2004).[12] The coefficients on the quality variables are all positive and significant with greater than 99 percent confidence. The coefficient estimates for the brand dummies (not shown) are also significant and indicate Apple is by far the most expensive brand, while Compaq and Packard are the least expensive brands. In all, we view the differences between the results here and those in DDOS (2004) as fairly minor, consistent with the use of more stringent conditions for inclusion of observations in the estimation sample and by the more parsimonious specification for the effects of age and time (which can be affected by increasing sample size over time).

Column (2) of table 3 shows results for the same specification estimated over 2003 to 2014. Looking at the later period, our estimates indicate that constant-quality

[10]We also attempted to include dummy variables for the presence of an optical drive (CD ROM or DVD) and a monitor. The optical drive dummy was not generally statitically significant. Although the monitor dummy was generally statistically significant, its presence did not seem to materially affect the estimates of quality-adjusted depreciation and price change.

[11]DDOS (2004) employ a more flexible specification that include dummies for each survey reference period and a polynomial up to the fourth power on a, producing estimates of how inflation varies over time and how depreciation varies over the life cycle of the PC.

[12]The average inflation rate and depreciation rates are obtained as $\exp(12\gamma) - 1$ and $\exp(12\phi) - 1$. For the (unadjusted) depreciation rate in DDOS (2004) we use $1 - (0.617)^{1/5}$.

prices of used desktops fell at an average annual rate of 14.1 percent, less than half the rate of decline in the earlier period. Meanwhile, depreciation rates appear similar in both subperiods, both around 13 percent per year. The baseline regression still fits the data quite well in the later period, but the adjusted R-squared (0.83) is a little lower than that for the earlier period (0.87). Bearing in mind the usual admonition against interpreting coefficient estimates on characteristics as literal shadow prices for these attributes (Erickson and Pakes, 2011), we observe that the estimated coefficients associated with the three measures of product characteristics in the post-2003 regressions are somewhat smaller than in the earlier period.

In the regression for the entire time period over which we have data (1985 to 2014), we included additional variables to allow the relationship between CPU speed and price to vary over the (roughly) two halves of the sample. Our choice of this specification was due, in part, to previous work by Byrne et al. (2015), in which the authors demonstrated that clockspeed rates (MHZ) for leading-edge CPU chips leveled off after the early 2000s, although machine performance continued to advance. Indeed, the evolution of product characteristics presented earlier in the data section show a noticeable slowing in the growth of clock speeds in the early 2000s, and accordingly, the relationship between CPU speeds and PC prices was notably different later in the 2000s through the present.[13] To be sure, the three characteristics are positively correlated. Nevertheless, when viewed together with the drop in the overall explanatory power of our quality variables, these findings raise some concern that the three characteristics we employ in our regressions may not be sufficient to control for overall quality changes over the entire sample period. In an effort to address this issue, we construct an additional control variable measuring the performance of the chip installed in each PC. In the bluebooks, information on the type of chip in each PC is often, though not always, included in the model description. Using this information, we assigned each CPU type to a 'chip family' and, in turn, to a set of performance scores.[14] We use the CPU benchmark tests published by System Performance Evaluation Corporation (SPEC), an industry consortium Henning (2007). These benchmarks are actual tasks chosen to

[13]In addition, when we estimated the baseline specification with a fixed coeffficient on clock speed over the full sample, the resulting coefficient was negative.

[14]We matched each CPU by its family and clock speed (rounded to two significant figures), and then accepted all matches where the PC introduction year was between one year before and 2 years after the CPU introduction year. We then computed the median score of all accepted matches, but drop cases where there were more than four possible matches and where the maximum score was more than 25 percent higher than the minium score of all matches.

be representative of user activity, such as file compression or graphics rendering. Our measure is the geometric mean of the SPEC integer and floating point scores.

Column (4) repeats the baseline specification estimated using only observations for which we have a non-missing performance score, and column (5) includes the additional performance score variable to control for quality. For desktop PCs, restricting the sample to those with non-missing performance scores reduces the sample size by roughly half. (We intend to expand the sample in the future by constructing imputing performance scores by regressing them on the other characteristics.) The coefficient on the performance variable is statistically significant, and the addition of this variable improves the overall fit of the regression. The effect on the estimates of constant-quality price changes and depreciation is noticeable: The implied annual depreciation rate is slower in the regression that includes performance scores (10.1 percent vs. 18.7 percent; see table 6), while constant-quality price changes are nore negative after adjusting for differences in performance scores (-26.6 vs. -18.9 percent, annual rate). Nevertheless, these comparisons should be treated with some caution since the count of observations with non-missing performance scores is much smaller than the overall sample.

Given the richness of our dataset and the evidence of wide fluctuations in constant-quality prices of used desktop PCs over the 1985-2014 period, we also tested an alternative specification where both the time and age variables were interacted with an indicator variable for (NBER-defined) expansions vs. recessions (including a band of 12 months before the start and after then end of the recessions).[15] As shown in column (6), our results imply that depreciation rates tend to be significantly smaller around recession periods, a pattern that suggests used PCs lose their value via obsolescence more slowly in these periods. As reported in table 6, while the depreciation rate is estimated to be 15.5 percent outside of recessions, annual depreciation is only 6.3 percent in periods around recessions. This, in turn, suggests that the productive capital stock of PCs tends to be less affected by the weakness in computer investment usually present in recessions than would otherwise be expected.

In column (7) of table 3, we looked for evidence of time-varying coefficients by examing a regression specification that allows the time and age coefficients to vary over three sub-periods of ten years or so. The coefficients on these additional variables all enter significantly, suggesting that both depreciation and constant-quality prices exhibited significantly different patterns over the three time periods. The implications

[15] Although not shown, we also include the recession indicator as an independent regressor.

of the time-varying coefficients, presented in table 8, indicate that depreciation rates were highest during the 1995-2004 period, precisely when quality adjusted prices fell the most. Intuitively, when rapid technical advances are occuring, one tends to observe faster declines of constant-quality prices, and faster depreciation. That being said, the difference between the rate of depreciation for 1995-2004 (15.9 percent) and the rate for 2005-2014 (13.9 percent) is fairly modest. Consistent with this pattern, figure x shows the close relationship between the average constant-quality inflation and depreciation rates over the time-period intervals considered.

3.2 Laptop PCs

The results for laptop PCs are only moderately different than those for desktop PCs, although somewhat surprisingly, the implied depreciation rates are generally lower for laptops than for desktop PCs. As seen in column (1) of table 4, the parsimonious specification of technical controls also fits the data quite well for laptops; CPU speed and RAM are important characteristics of the price of used laptop PCs, while the coefficient on HD is very small and with the wrong sign (a dummy for the presence of a CD ROM/DVD does not enter significantly). As with desktop PCs, the estimated depreciation rate after controlling for performance scores appears noticeably slower than in the regression with only three characteristics (6.1 vs. 14.1 percent) (see table 6). Slower depreciation rates were found for recessions v. expansions (7.1 percent vs. 10.4 percent), though by a more modest degree than for desktop PCs. And, roughly the same slowdown in depreciation rates for desktop PCs since 1994 was also found for laptops. The implied constant-quality prices of used laptops fell at a faster annual pace of 22.0 percent early in the sample (2001-2004) than the 17.4 percent rate of decline over the 2005-2014 period.

3.3 Tablet PCs

Table 5 presents the baseline regression estimates for tablet PCs. All three main characteristics are important determinants of the price of used tablets, and most noticeably the processor speed and the hard drive capacity. Constant-quality prices for tablets fall at an annual pace of 17.8 percent, about the same as the rate of decline in used laptop PCs (over 2005-2014); over roughly comparable periods, the depreciation rate for tablets (12.7 percent) is in between the rates for desktops and laptops (14 per-

cent and 9 percent, respectively). Recognizing the special role played by Apple as an innovator in this market, we ran separate regressions for Apple and for other brands (columns 2 and 3). While quality-adjusted prices do appear to fall faster for Apple tablets than for other tablet brands, the rates of depreciation for the two groups are little different. We do not have in hand performance benchmarks for tablets, and this extension is left for future work. In addition, the tablet data will allow us to run a panel regression that controls for individual model fixed effects, which will make for an interesting comparison with the hedonic regression results.

4 Macroeconomic Implications for Capital Stocks and Productivity Growth

5 Conclusion

We use a consistently-constructed dataset of used personal computer prices spanning nearly the entire history of the industry to simultaneously identify the rate of depreciation for the installed base of computers and the constant-quality price trend for new PCs. This allows us to examine the joint movement of these series over time.

In addition, the long time series permits us to consider the time-variation of depreciation rates and whether the assumption in the national accounts of an invariant rate is appropriate. We find for desktops and laptops that depreciation rates do appear to have been especially fast during the period covered by the Doms et al. (2004), though the difference relative to the more recent period is relatively modest.

We note that a parsimonious specification for technical control variables provides a rather good fit in our regressions but that controlling for direct measures of performance on tasks of interest to the user does make a material difference to the resulting depreciation rate esitmates.

We also observe the entry and rapid market penetration of desktop, laptop and tablet computers. While a broader dataset with a multitude of platforms for different products would be needed to nail down these questions, these data do shed some light on the role of platform maturity and the entry of competing platforms on depreciation.

Finally, the paper provides an alternative to official sources of information about recent trends for computer prices at a time when the issue is of some importance. Our preliminary results indicate that some slowdown in PC price declines has occurred

since the end of the IT boom, but to a significantly lesser degree than indicated by the investment index used in the NIPAs.

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Table 1: Timing of Bluebook Price Observations: Desktops and Laptops

Bluebook edition	Reference Period	Time Period Index
1985	January-June 1985	1985-03
1986	January-June 1986	1986-03
1987	January-June 1987	1987-03
1988	January-June 1988	1988-03
1989	January-June 1989	1989-03
1990	January-June 1990	1990-03
1991	January-June 1991	1991-03
1992	January-June 1992	1992-03
1993Q4	July-September 1993	1993-08
1994Q4	July-September 1994	1994-08
1995Q1	October-December 1994	1994-11
1996Q1	October-December 1995	1995-11
1997Q1	October-December 1996	1996-11
1998Q1	October-December 1997	1997-11
1999Q1	October-December 1998	1998-11
2000Q1	October-December 1999	1999-11
2001Q1	October-December 2000	2000-11
2002Q1	October-December 2001	2001-11
2003Q1	October-December 2002	2002-11
2004Q3	April-June 2004	2004-05
2005Q4	July-September 2005	2005-08
2006Q4	July-September 2006	2006-08
electronic	February 2007	2007-02
electronic	July 2007	2007-07
electronic	February 2008	2008-02
electronic	April 2008	2008-04
electronic	April 2009	2009-04
electronic	October 2009	2009-10
electronic	February 2010	2010-02
electronic	November 2010	2010-11
electronic	February 2011	2011-02
electronic	November 2011	2011-11
electronic	February 2012	2012-02
electronic	November 2012	2012-11
electronic	February 2013	2013-02
electronic	November 2013	2013-11
electronic	February 2014	2014-02
electronic	November 2014	2014-11

Table 2: Summary Statistics by Year

(a) Desktops

Year	**Obs.** (count)	**ln(p)** (median)	**Age** (median)	**ln(MHZ)** (median)	**ln(RAM)** (median)	**ln(HD)** (median)
1985-1989	141	7.7	33.0	2.1	0.7	-3.5
1990-1994	2,146	6.5	29.0	3.2	1.1	-2.1
1995-1999	5,224	5.6	41.0	4.2	2.2	-1.0
2000-2004	6,821	5.2	41.0	6.1	4.2	2.3
2005-2009	10,259	4.6	65.0	6.8	4.9	3.0
2010-2014	12,557	5.4	48.0	7.9	8.0	5.8
Total	37,148	5.3	50.0	6.8	4.9	3.0

(b) Laptops

Year	**Obs.** (count)	**ln(p)** (median)	**Age** (median)	**ln(MHZ)** (median)	**ln(RAM)** (median)	**ln(HD)** (median)
2000-2002	2,403	6.3	29.0	6.2	4.2	1.8
2003-2005	2,919	5.7	47.0	6.5	4.6	2.3
2006-2008	4,277	5.3	62.0	6.7	4.9	3.0
2009-2011	6,437	5.7	44.0	7.5	6.9	4.4
2012-2014	14,964	5.5	41.0	7.6	8.3	5.8
Total	31,000	5.6	41.0	7.4	6.9	4.6

(c) Tablets

Year	**Obs.** (count)	**ln(p)** (median)	**Age** (median)	**ln(MHZ)** (median)	**ln(RAM)** (median)	**ln(HD)** (median)
2007-2008	19	6.5	19.0	7.1	6.2	3.4
2009-2010	152	6.5	22.5	6.9	6.2	3.5
2011-2012	861	6.1	15.0	6.9	6.2	3.5
2013-2014	2,914	5.9	17.0	7.2	6.9	3.5
Total	3,946	6.0	17.0	7.0	6.9	3.5

Note: Year is the reference year for the used price, ln(p) is the log of the used price, ln(MHZ) is the log of the CPU speed in MHZ, ln(RAM) is the log of the RAM in MB, and ln(HD) is the log of the hard disk storage capacity in GB.

Table 3: Hedonic Regressions: Desktop PCs

	(1) 1985-2002	(2) 2003-2014	(3) 1985-2014	(4) 1995-2014	(5) 1995-2014	(6) 1985-2014	(7) 1985-2014
ln(RAM)	0.383***	0.309***	0.438***	0.340***	0.285***	0.426***	0.352***
	(32.25)	(49.77)	(64.06)	(36.10)	(30.81)	(64.71)	(65.22)
ln(HD)	0.147***	0.147***	0.127***	0.108***	0.0602***	0.131***	0.134***
	(16.24)	(23.28)	(19.24)	(12.02)	(6.85)	(20.60)	(25.98)
ln(MHZ)	0.431***	0.334***	0.0129	0.321***	0.336***	0.155***	0.405***
	(25.29)	(44.04)	(1.82)	(28.16)	(30.47)	(21.00)	(52.17)
Time	-0.0416***	-0.0127***	-0.0219***	-0.0174***	-0.0258***	-0.0252***	-0.0107***
	(-116.60)	(-76.04)	(-111.85)	(-56.83)	(-68.00)	(-125.58)	(-59.89)
Age	-0.0112***	-0.0117***	-0.0130***	-0.0172***	-0.00885***	-0.0140***	-0.0125***
	(-28.54)	(-69.58)	(-65.63)	(-55.76)	(-23.28)	(-71.53)	(-72.55)
Post-2003 * ln(MHZ)			0.415***	0.00697	-0.192***	0.266***	-0.000600
			(17.71)	(0.16)	(-4.39)	(11.65)	(-0.03)
ln(Performance)					0.464***		
					(35.36)		
Recession * Time						-0.00135***	
						(-11.42)	
Recession * Age						0.00859***	
						(36.35)	
1985-1994 * Time							-0.0235***
							(-52.31)
1995-2004 * Time							-0.0286***
							(-109.27)
1985-1994 * Age							0.00583***
							(12.66)
1995-2004 * Age							-0.00196***
							(-7.16)
N	12410	24738	37148	17710	17710	37148	37148
adj. R^2	0.869	0.829	0.757	0.817	0.829	0.775	0.853

t statistics in parentheses

Notes: A constant and dummies for brand, time-period, and/or recessions are included in some cases but not reported.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4: Hedonic Regressions: Laptop PCs

	(1)	(2)	(3)	(4)	(5)
	2001-2014	2001-2014	2001-2014	2001-2014	2001-2014
ln(RAM)	0.295***	0.161***	0.166***	0.302***	0.295***
	(50.38)	(17.41)	(18.83)	(52.14)	(50.26)
ln(HD)	-0.0145*	-0.0422***	-0.0306**	-0.0160*	-0.0132
	(-2.05)	(-3.98)	(-3.04)	(-2.29)	(-1.88)
ln(MHZ)	0.544***	0.687***	0.564***	0.571***	0.546***
	(81.52)	(64.24)	(52.62)	(81.50)	(73.57)
Time	-0.0165***	-0.0130***	-0.0200***	-0.0158***	-0.0159***
	(-107.32)	(-47.68)	(-61.70)	(-98.36)	(-100.24)
Age	-0.00862***	-0.0127***	-0.00527***	-0.00912***	-0.00808***
	(-55.05)	(-44.63)	(-15.57)	(-56.52)	(-50.96)
ln(Performance)			0.368***		
			(35.94)		
Recession * Time				-0.00159***	
				(-10.69)	
Recession * Age				0.00301***	
				(16.47)	
1995-2004 * Time					-0.00481***
					(-8.12)
1995-2004 * Age					-0.00264***
					(-6.84)
N	30999	12004	12004	30999	30999
adj. R^2	0.755	0.810	0.828	0.761	0.757

t statistics in parentheses

Notes: A constant and dummies for brand, time-period, and/or recessions are included in some cases but not reported.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5: Hedonic Regressions: Tablet PCs

	(1) 2007-2014	(2) Apple	(3) Other
ln(RAM)	0.365***	0.280***	0.247***
	(32.14)	(25.25)	(6.03)
ln(HD)	0.223***	0.195***	0.389***
	(43.22)	(58.62)	(14.57)
ln(MHZ)	0.108***	0.114***	0.359***
	(6.97)	(9.39)	(5.94)
3G	0.132***	0.0993***	-0.0898*
	(11.32)	(14.38)	(-2.17)
4G	-0.0644***	0.0199*	
	(-4.75)	(2.31)	
Monitor Size	0.0306***	0.0664***	0.00126
	(8.44)	(13.54)	(0.16)
Time	-0.0163***	-0.0161***	-0.0133***
	(-41.63)	(-28.81)	(-13.63)
Age	-0.0113***	-0.0126***	-0.0125***
	(-32.53)	(-23.02)	(-13.78)
N	3946	2954	992
adj. R^2	0.834	0.905	0.790

t statistics in parentheses

Notes: A constant and dummies for brand, time-period, and/or recessions are included in some cases but not reported.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6: Alternative Estimates of Depreciation

Regression	Description	Desktops	Laptops
1	Early sample	-12.6	
2	Late sample	-13.1	
3	Full sample	-14.5	-9.8
4	Restricted sample (performance scores)	-18.7	-14.1
5	With performance scores	-10.1	-6.1
6	Business cycle dummy: Expansions	-15.5	-10.4
6	Business cycle dummy: Recessions	-6.3	-7.1
7	Ten-year bin: 1985-1994	-7.7	
7	Ten-year bin: 1995-2004	-15.9	-12.1
7	Ten-year bin: 2005-2014	-13.9	-9.2

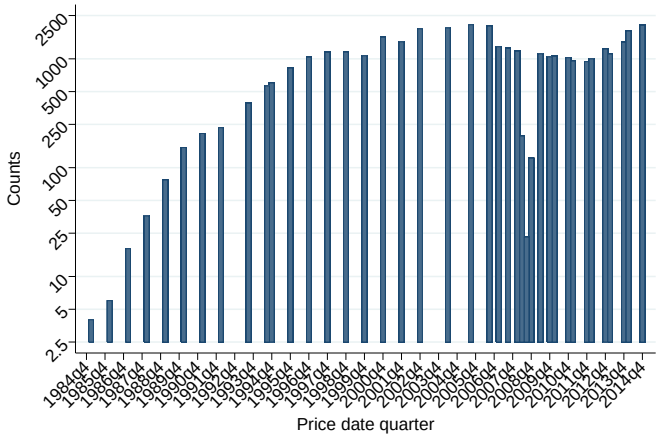
Table 7: Alternative Estimates of Constant-Quality Price Changes

Regression	Description	Desktops	Laptops
1	Early sample	-39.3	
2	Late sample	-14.1	
3	Full sample	-23.1	-18.0
4	Restricted sample (performance scores)	-18.9	-14.5
5	With performance scores	-26.6	-21.4
6	Business cycle dummy: Expansions	-26.1	-17.3
6	Business cycle dummy: Recessions	-27.3	-18.9
7	Ten-year bin: 1985-1994	-33.7	
7	Ten-year bin: 1995-2004	-37.5	-22.0
7	Ten-year bin: 2005-2014	-12.0	-17.4

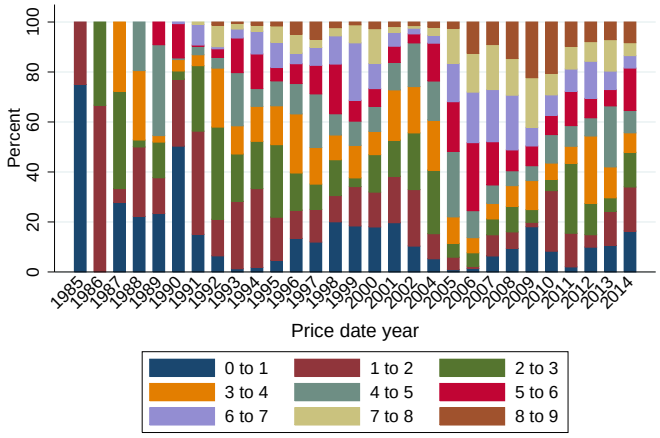
Table 8: Results for Time-Varying Depreciation and Price Changes

Time period	Desktops	Laptops
Depreciation		
1985-1994	-7.7	
1995-2004	-15.9	-12.1
2005-2014	-13.9	-9.2
Constant-quality price change		
1985-1994	-33.7	
1995-2004	-37.5	-22.0
2005-2014	-12.0	-17.4

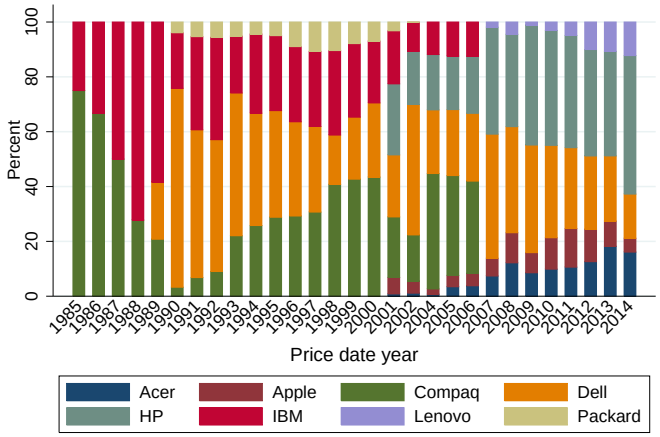
Figure 1: Histogram and Age/Brand Distribution: Desktops



(a) Histogram

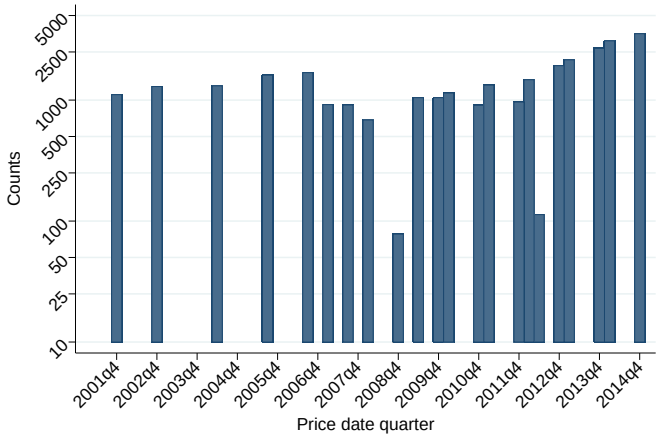


(b) Age distribution by price year

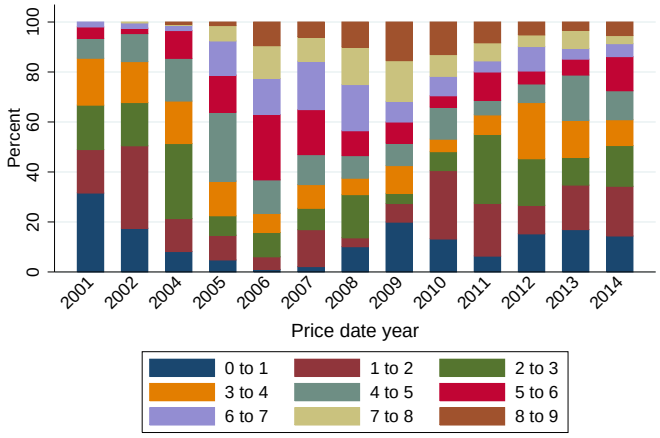


(c) Brand distribution by price year

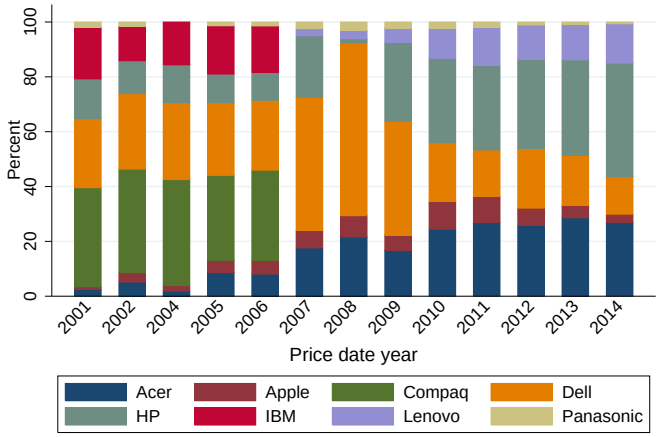
Figure 2: Histogram and Age/Brand Distribution: Laptops



(a) Histogram

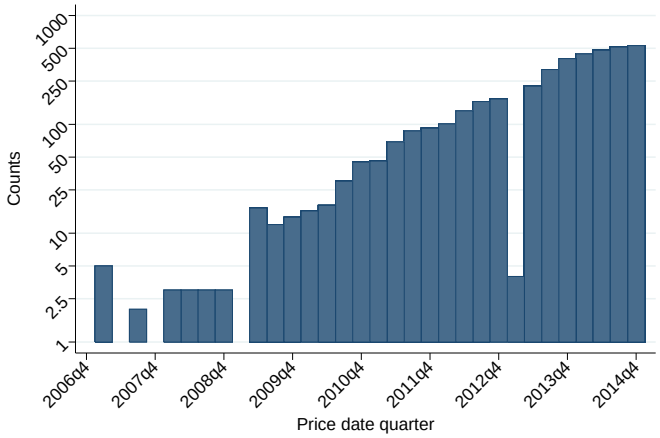


(b) Age distribution by price year

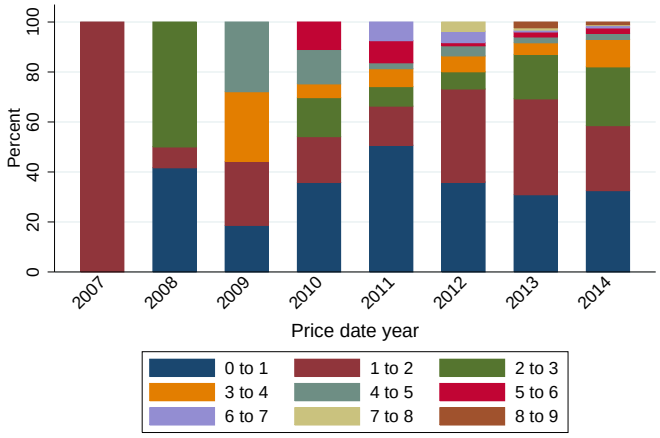


(c) Brand distribution by price year

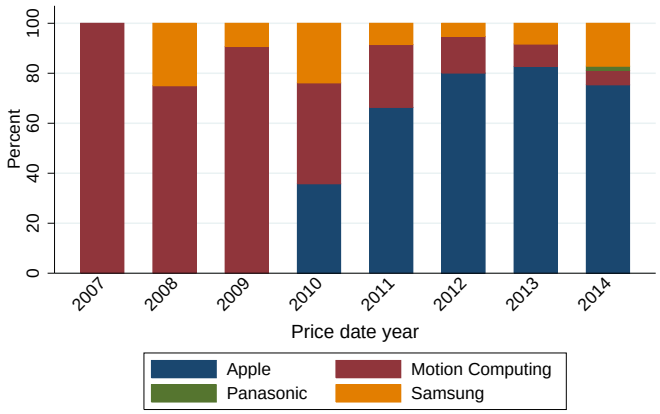
Figure 3: Histogram and Age/Brand Distribution: Tablets



(a) Histogram

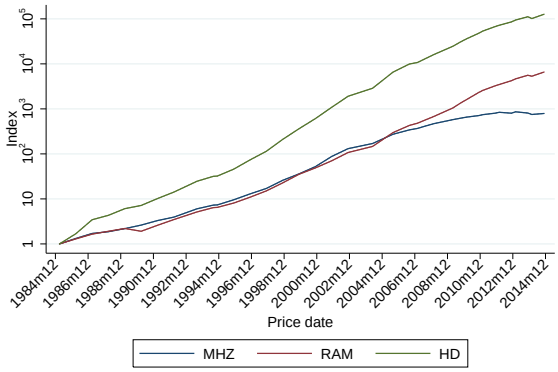


(b) Age distribution by price year

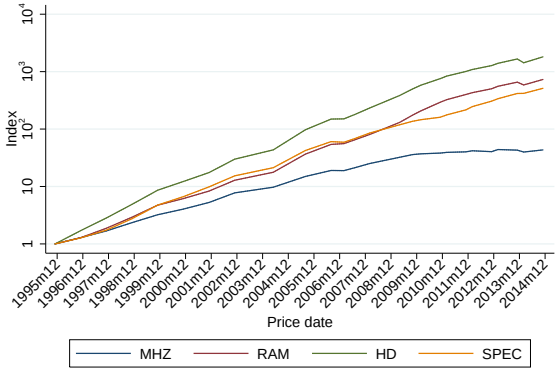


(c) Brand distribution by price year

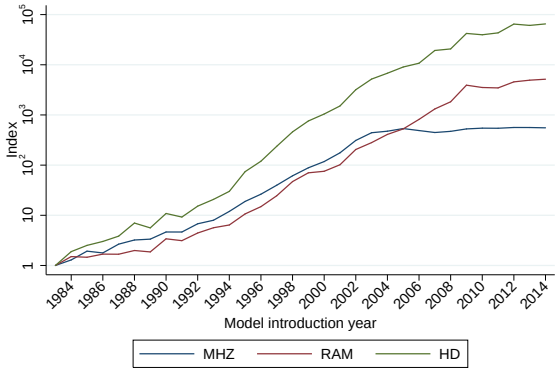
Figure 4: Evolution of PC Characteristics: Desktops



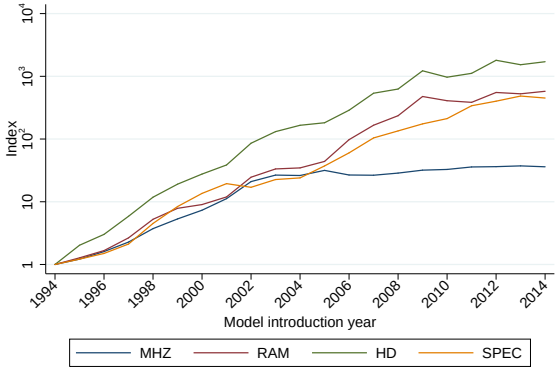
(a) By price date, all sample



(b) By price date, specs sample

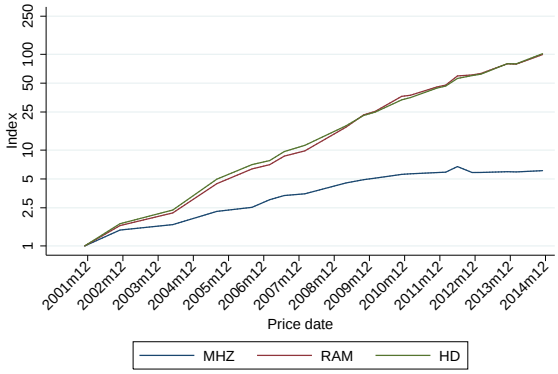


(c) By shipment year, all sample

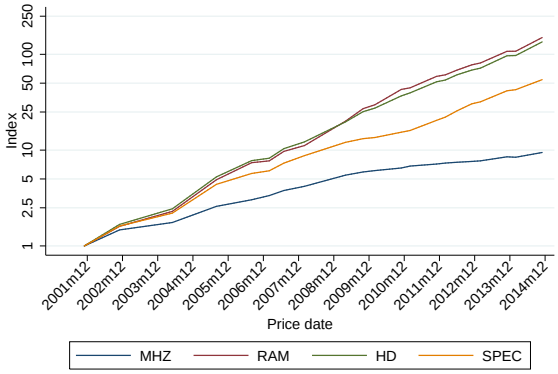


(d) By shipment year, specs sample

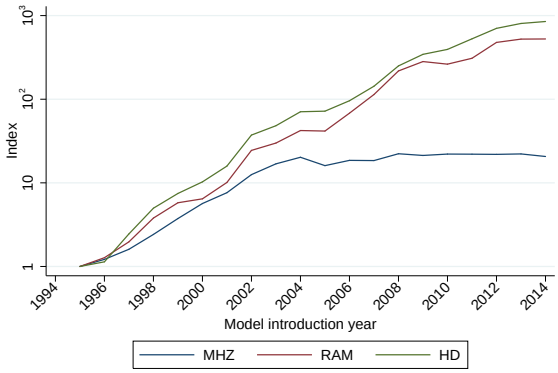
Figure 5: Evolution of PC Characteristics: Laptops



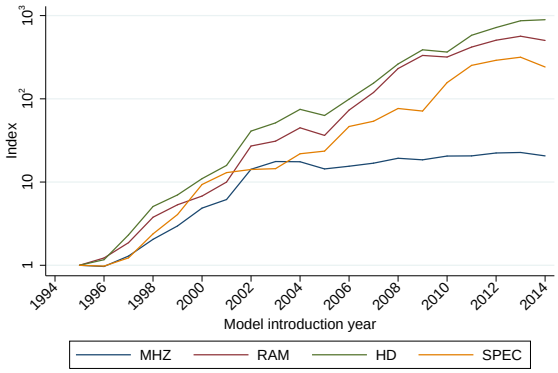
(a) By price date, all sample



(b) By price date, specs sample

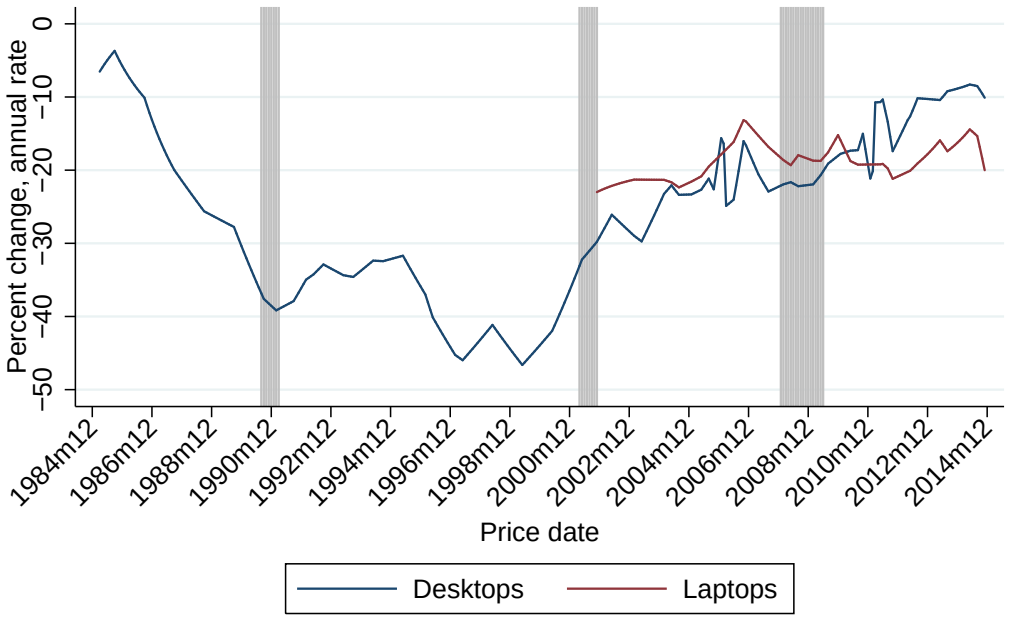


(c) By shipment year, all sample



(d) By shipment year, specs sample

Figure 6: Quality-Adjusted Inflation of Used PCs



Note: Five−year centered moving average. Shaded bars represent periods of recession as defined by the NBER.

Figure 7: Age-Price Profiles for Used Desktops