■ **University of Illinois at Urbana-Champaign**
College of Commerce and Business Administration
Office of Research

# PRICING OVER THE PRODUCT CYCLE: THE TRANSITION FROM THE 486 TO THE PENTIUM PROCESSOR

George Deltas
Eleftherios Zacharias

**Office of Research Working Paper Number 99-0100**

# Pricing over the Product Cycle:

# The Transition from the 486 to the Pentium Processor.

George Deltas

University of Illinois, Urbana-Champaign

1206 South Sixth Street, Champaign, IL 61820.
Tel. No: 217-333-4586.
Email: deltas@uiuc.edu.
http://www.staff.uiuc.edu/~deltas

Eleftherios Zacharias

University of Illinois, Urbana-Champaign

1206 South Sixth Street, Champaign, IL 61820
Tel. No: 217-359-5775.
Email: lefteris@uiuc.edu.

January 1999

We are indebted to Ian Cockburn, Shane Greenstein, and Nancy Rose for their comments and suggestions. We would also like to thank Howard Berkson, Tom Cottrell, Francisco Cribari-Neto, Bronwyn Hall, Wally Hendricks, Roger Koenker, George Norman, Scott Stern, and Lawrence White. The participants of the NBER Universities Research Conference “Competition and Organization in Technology-Intensive Industries” and of the University of Illinois Econometrics/Applied Economics Workshop offered many helpful comments and discussion. We alone are responsible for any errors.

# *Abstract*

Using a high frequency data-set of advertized prices in the personal computer industry, we find that firms which introduced Pentium computers late in the “Buy Direct” segment of the market command a higher price premium compared to early entrants. This is true even among firms which have the same price premium for their 486 computers, but is more pronounced for high quality firms. Over time, the difference in the Pentium price premia of the late versus the early entrants decline to the levels of the difference in the corresponding 486 price premia. The decline in the relative Pentium price premia contributes to a decline in overall price dispersion, while price dispersion for 486 computers remains constant. These results suggest that late entrants reap short run rents from these consumers that are loyal enough to them to have waited until their entry in order to purchase. They also suggest a rapidly declining price premium for quality over the product cycle. In light of these findings, brand coefficients in hedonic regressions using high frequency data should not be interpreted as capturing unobserved quality only.



JEL Classification Codes: L11, L63.
Keywords: Sequential Entry, Strategic Pricing, Product Cycle.

## 1. Introduction.

Consider the introduction of a new product or a technological innovation that substantially improves an existing product. Firms often differ in the timing of introduction of the new product or adoption of the technological innovation either for strategic reasons or due to other factors beyond their control.[1] In general, the potential adopters will also differ in their reputation for offering high quality products and in their assessment of the market demand for the new innovation. These differences will directly impact the pricing decisions of these firms not only when they first introduce the product, but potentially over the entire product cycle.

Consider first the impact of differences in the timing of entry on prices. If consumers care only about the objective characteristics of the products they purchase, as in monopolistic competition and location in the characteristic space models, then inter-firm price differences will not depend on the timing of adoption of a technological innovation.[2] However, if consumers are characterized by brand loyalty, late entrants will choose to charge a higher price when they introduce their products relative to the prices charged by early entrants at the same point in time. This enables late entrants to reap short run rents from these consumers that are loyal enough to them to have waited until their entry in order to purchase.[3]

Consider next the impact of differences in product quality on pricing over the product cycle. High quality firms may initially charge relatively high prices if the consumers who are quality sensitive are high valuation consumers who purchase early. In addition, consumers may become

---

[1] For example, one firm may be the first one to innovate, with others copying or reverse engineering the innovation. Alternatively, the innovator may license the technology to an initially small number of firms and expand the number of licenses over time.

[2] In multi-period versions of monopolistic competition firms with identical products would charge the same price regardless of their entry sequence. The markup would be a function of the number of firms currently producing the new product. For a dynamic model of this flavor, allowing for certain types of firm asymmetries, see Eliashberg and Jeuland (1986). In multi-period versions of location models, the price of a product would be a function of the product's characteristics only.

[3] We implicitly assume that a firm can price discriminate between high and low valuation consumers by being able to commit to a price for a period of time. In the absence of such a commitment such inter-temporal price discrimination would not be attainable. [Coase (1972).] In Appendix A we develop a two period duopoly model that formalizes this intuition.

progressively less willing to pay a quality premium because they perceive differences in reputation for quality to be less important when firms have accumulated a substantial experience in manufacturing the products. Finally, firm differences in the assessment of market demand for the product will translate in differences in their pricing strategies. Over time, firms' assessment of demand conditions will tend to converge, reducing price dispersion.

In this paper we use data from personal computer industry during the transition from the 486 to the Pentium processors to investigate how the differences in the timing of introduction of a new technology and differences in the reputation for quality impact the pricing strategies of firms.[4] In particular, we investigate (i) whether relative firm prices, adjusted for the computer configuration, are systematically related to the order of introduction of Pentium-based computers, (ii) whether price dispersion decreases over the product-cycle, (iii) whether the implicit price for quality changes as the new technology matures, and (iv) whether firms are able to charge differential component prices for the two product lines.

We show that firms which introduce Pentium-based computers relatively late charge higher prices (for Pentium computers) relative to early entrants and that these price differences decline over time. This is true even for firms which charge similar prices in their 486 line-up: Amongst these firms, the late entrants charged higher prices, by about 5-7%, in the first two quarters following their entry. We also show that high quality firms command a declining price premium for Pentium-based computers: Pentium computers sold by these firms are initially priced at 65% or $2,000 higher than otherwise identical computers sold by other firms with this price gap dropping to about 15% or $400 after 1 ½ years. On the contrary, their price premium for 486-based computers remains broadly constant throughout this period at about 25% or $400. Overall price dispersion remains constant for 486 computers but declines for the Pentium machines. Finally, we show that computer component prices for the two product lines are not systematically different.

[4] Our source of both price and model availability data is the Buy Direct press. Therefore, entry and pricing strategy refer to this segment of the market only.

The higher Pentium prices charged (at least initially) by firms which introduce such computers relatively late provide support for the presence of consumers with brand loyalty: Consumers who have resisted purchasing from the early entrants are disproportionately consumers who are loyal to the late entrants. When the late entrants produce their own models they can extract rents from these consumers by initially charging a high price. As the proportion of loyal consumers declines, the price premium of the late entrants declines as well.[5] The declining price premium of high quality firms indicates that the value of quality and reliability may be higher at the introduction of the new technology than at later stages. It may also indicate that consumers may perceive a declining quality differential between firms as the new technology becomes more established. The reduction over time in the price differences between early and late entrants and the declining price premium of the high quality firms result in a decline in overall price dispersion. Once these two price effects are accounted for, residual inter-firm price variance remains constant over the product cycle and equals the price variance for the 486 product lines. This residual price variance captures, among others, differences in the firms' perceptions of the market environment and their production capabilities. Its constancy over the product cycle suggests that the contribution of these factors on price variance does not decline as the market matures. Finally, the conjecture that computer manufacturers can not price discriminate by differentially pricing computer components in the old and new generation personal computers is confirmed by the absence of substantial differences in component pricing between 486 and Pentium computers.

Focusing on the personal computer industry confers a number of advantages. First, progress in the most important component of the personal computer, the microprocessor, is not determined by computer manufacturers, but rather by semiconductor manufacturers (mainly Intel) which do not sell computers themselves. This implies that the choice of the technology that is incorporated in a new model is not a strategic variable. Only the timing of introduction and pricing of the new models are variables in the control of the manufacturers. This allows us to focus on the strategic

[5] This is the same insight that underlies the pricing strategy of a multi period monopolist. When the firm can commit to a price for a finite length of time, the optimal price will be a declining over time. High value consumers purchase early, low value consumers purchase late. See, among others, Stokey (1979), Kahn (1986) and Bagnoli, Salant, and Swierzbinski (1989).

effects of entry and pricing alone. Second, due to the open architecture of IBM compatible computers, consumers can adjust many of the key features of the personal computers they purchase buy buying cards, peripherals, and other components from a very competitive market for unbundled components. This limits the extent to which manufacturers can use the introduction of the new technology to price discriminate by differentially pricing the components for the new versus the old model and results in uni-dimensional firm pricing strategies. [6] Finally, this industry is characterized by very rapid technological progress. Product cycles are measured in months instead of years. This implies, that the effect of within industry factors in determining the pricing patterns will swamp any effects from the rest of the economy.

Our results also have implications for the interpretation of firm dummies in hedonic regressions. Firm dummies are frequently employed to capture the effects of unobserved quality and other product characteristics that vary across firms but are likely to be the same for the products of the same firm.[7] Firms with low values for their dummy variables are interpreted as low quality firms and vice versa. If, however, firm identity matters over and above any product characteristics, the data is of sufficiently high frequency, and product introduction dates differ across firms, then a firm dummy captures more than unobserved quality.[8] When multi-period price *and* quantity data is available, empirical models that estimate the structural parameters of consumer preferences can capture the effects of differences in the timing of entry. This can be done by explicitly incorporating as a consumer choice the option to wait and purchase a product introduced at a later date. One could, thus, estimate the degree of inter-temporal substitution between products of the same brand and between products of different brands.[9]

---

[6] As we discussed above, this conjecture is supported by the data.

[7] See, for example, Stavins (1995), Brendt, Griliches and Rappaport (1995), and Berndt and Griliches (1993).

[8] Lerner (1995) is another example of a hedonic analysis where regression residuals are given strategic interpretation. In particular, he uses them to provide evidence that hard drive manufacturers put pressure on financially weak rivals by aggressively pricing their products.

[9] Bresnahan, Stern and Trajtenberg (1997) is an example of estimation of structural parameters of consumer preferences. However, the inter-temporal substitution between products of the same or different firms is not estimated.

## 2. Data.

Our main sources of data are the advertized prices and features of personal computers in *PC Magazine*.[10] We collected data on the first issue of every month from January of 1993 to December of 1995. This period includes the last three years of the 486 based computers and the first two years of the Pentium based computers.[11] Since our focus is to a large extent the evolution of brand premia, we needed data for firms for which there are repeat observations over time. We therefore limited our attention to the following firms: ACER, AUSTIN, COMPAQ, COMTRADE, DELL,[12] GATEWAY 2000, IBM, MICRON, MIDWEST MICRO, and ZEOS.[13] The prices we collected are the list prices as they appeared in the ads of these manufacturers.[14]

An observation consists of the price of a computer and its associated features. The features that we included in our analysis are, the identity of the manufacturer, the processor type and its clock speed (in MHz), the size of the hard drive (in MB), the size of the RAM (in MB), the size of the screen (in inches), the presence of a CD-ROM, and the presence of a multimedia kit that includes speakers and a sound card.[15] We did not collect any information that indicated quality differentials between listings, both across firms and time. For instance, we did not include information on the speed of the CD-ROM or the access time of the hard drives. We also did not

---

[10] This is the main personal computer magazine. We have also done spot checks of the quotes in other magazines and we found them to be the same.

[11] There were a very small number of 386 and Pentium Pro based computers in our sample. These were not used in our analysis and will not be further discussed.

[12] We did not include the DELL Optiplex models since this product line is targeting the business market.

[13] We did *not* incorporate prices listed by computer wholesalers such as Insight Direct and Computer Discount Warehouse. INSIGHT does make its own computers, but did not advertize them frequently enough to merit inclusion in our data-set. MIDWEST MICRO also sells computers made by other manufacturers. We did not include these price quotes either.

[14] For the Buy Direct segment of the market list prices are essentially equal to transactions prices for purchases by individual consumers.

[15] We also collected data on the graphics card memory, length of warranty, floppy drives, and type of case. We did not include these in the analysis because the size of graphics memory and warranty information is frequently omitted, the 5 ½ inch floppy drives are phased out in the early part of this period, and the type of case is neither always explicitly mentioned nor does it affect the price in most cases. Our results appear to be robust to the inclusion of graphics card memory in the analysis.

collect any information on bundled sofware, bus slots, chipset design, and delivery time. Systematic differences in these features and in the quality of components will be captured by the relative brand premia.

In a typical advertizement, a firm lists the price and all the features for a few models. In the same advertizement, the firm also lists the incremental price of incorporating some features on these "base" models. These "upgrades" are often available for all models, but other times available to only some of them.[16] Every possible combination that involved an upgrade of a major component has been used to create a separate observation.[17] We also included upgrades that incorporated a better technology when this was also associated with an increase in the price.[18]

Altogether, our data-set consists of 10474 observations, of which 6283 correspond to 486 computers and 4191 to PENTIUM computers. The distribution of these observations over the 10 firms in our data-set is very uneven. This mostly reflects the difference in advertizing styles among these firms: Some firms, most notably ZEOS, list a large number of possible upgrades while others, like Compaq, list only a minimal number of configurations. To a lesser extent, it reflects the frequency of advertizing in the issues of *PC Magazine*. Some companies did not advertize or list particular model information on every issue. For example, COMPAQ advertized in only 31 out 36 issues, IBM in only 28, and COMTRADE in a mere 23 issues.[19] Table 1 below shows the distribution of observations over brands and processor types for the three years in our data-set.

---

[16] Generally, firms are willing to ship computers in configurations other than those advertized. However, delivery times may be somewhat longer compared to those for models that are listed.

[17] We did not include upgrades or computers of 124 MB or more of RAM, 19 or more inches of monitor, and more than 4 Gigabytes of hard drive. These are likely to belong to a very different market segment. Using the same line of thought, we excluded all servers from the data-set.

[18] For example, in the MIDWEST MICRO ads we have upgrades of the 15" SVGA 0.28 Digital Color Monitor screens to either 15" screens of the more advanced technology (0.26 1600 x 1200 ExactMatch Color Monitor) or to a 17" screen of the same technology. The first upgrade contributes essentially to the error term, as value of the RHS variables is the same for both observations, whereas the second upgrade involves a change of both price and the RHS variables. However, we were not exhaustive in including all the upgrades, e.g., we did not incorporate upgrades in the keyboard of MIDWEST MICRO.

[19] Only five firms, ZEOS, GATEWAY, MICRON, AUSTIN, and DELL appear on all, or almost all issues.

**Table 1.** Observations by Brand, year, and processor type.

| BRAND | 1993 | | 1994 | | 1995 | |
|---|---|---|---|---|---|---|
| | 486 | Pentium | 486 | Pentium | 486 | Pentium |
| Acer | 38 | 0 | 99 | 66 | 5 | 74 |
| Austin | 86 | 3 | 131 | 83 | 44 | 112 |
| Compaq | 61 | 0 | 44 | 2 | 11 | 40 |
| Comtrade | 356 | 0 | 188 | 188 | 52 | 113 |
| Dell | 153 | 3 | 80 | 63 | 19 | 116 |
| Gateway | 250 | 15 | 169 | 108 | 51 | 226 |
| IBM | 149 | 0 | 317 | 11 | 30 | 7 |
| Micron | 121 | 0 | 235 | 270 | 54 | 293 |
| Midwest Micro | 93 | 0 | 204 | 85 | 155 | 301 |
| Zeos | 1015 | 0 | 1440 | 626 | 633 | 1386 |
| TOTAL | 2322 | 21 | 2907 | 1502 | 1054 | 2668 |

Since the most important characteristic of a personal computer is its processor we define a model to be an offering of a particular processor by a particular brand. We can, therefore, organize our data-set in terms of model-observations which are all processor-brand-month combinations. That is, all Pentium 90 computers offered by Dell in July represent a single model-observation. We later use the concept of model-observations to run weighted regressions, with the weights being the inverse of the number of observations in a model-observation. Table 2 below shows the number of model-observations by brand, year, and processor type. One apparent fact is that the distribution of model-observations across firms is much more even than the distribution of observations. For example, ZEOS dominates the other firms in term of observations, but in terms of model-observations the difference between ZEOS and the other firms is much smaller.

The timing of introduction of Pentium computers in a firm's advertisements in *PC Magazine* can be seen in Figure 1 which plots the percentage of a firm's quotes that correspond to Pentium models. The transition from the 486 to the Pentium computers is smooth for most of the firms over the sample period with two notable exceptions: IBM and COMPAQ are late in advertizing

**Table 2.** Number of model-observation by brand, year, and processor type.

| BRAND | 1993 | | 1994 | | 1995 | |
|---|---|---|---|---|---|---|
| | 486 | Pentium | 486 | Pentium | 486 | Pentium |
| Acer | 16 | 0 | 25 | 18 | 5 | 35 |
| Austin | 43 | 2 | 24 | 23 | 10 | 36 |
| Compaq | 27 | 0 | 28 | 2 | 11 | 18 |
| Comtrade | 28 | 0 | 19 | 17 | 6 | 12 |
| Dell | 46 | 1 | 36 | 19 | 10 | 46 |
| Gateway | 40 | 3 | 27 | 27 | 10 | 52 |
| IBM | 29 | 0 | 39 | 4 | 12 | 6 |
| Micron | 25 | 0 | 35 | 21 | 20 | 50 |
| Midwest Micro | 18 | 0 | 41 | 24 | 22 | 48 |
| Zeos | 48 | 0 | 57 | 31 | 34 | 59 |
| TOTAL | 320 | 6 | 331 | 186 | 140 | 362 |

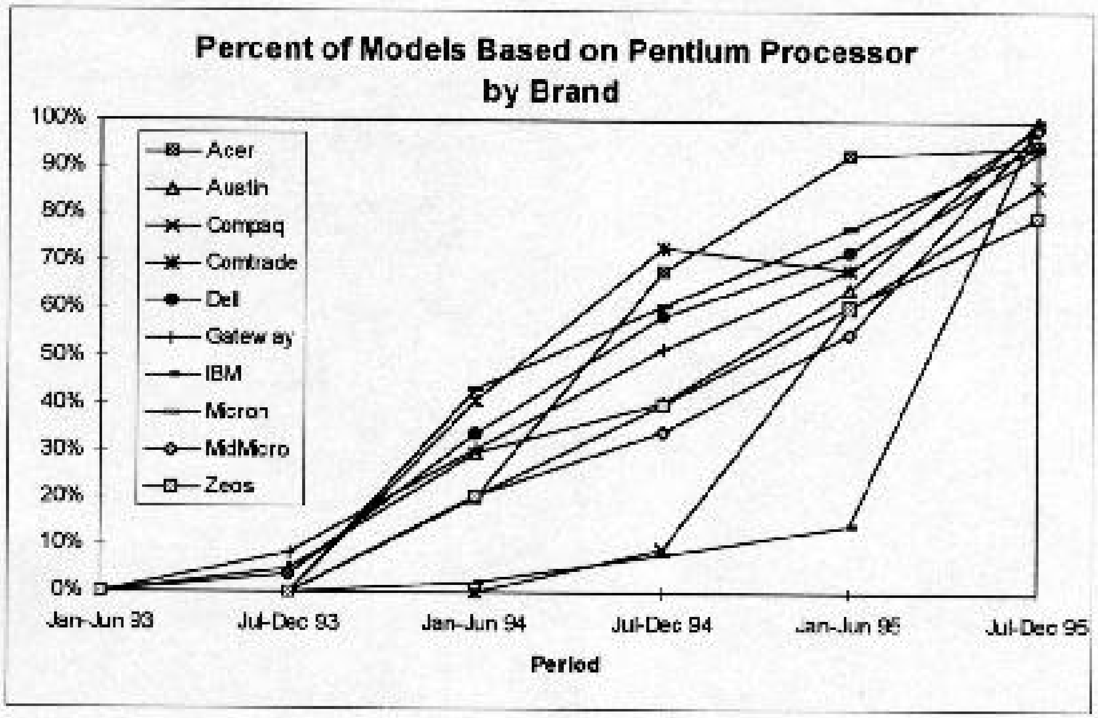



Figure 1

Pentium based computers in large numbers but they complete the transition very rapidly. We should emphasize, however, that the date a model was first advertized in the pages of *PC Magazine* does not in general correspond to its addition in a firm's product line. For example, both IBM and COMPAQ introduced Pentiums half a year or more before the first date of advertizement [see *PC WORLD*, June 1993, Hogan (1994)].

## 3. Model Specification and Estimation Procedure.

Our estimation methodology takes advantage of the richness of our data-set. We divide our observations in 12 data-sets each one corresponding to one calender quarter. We further divide these data-sets by processor type. This gives us a total of 20 data-sets.[20] We obtain estimates of brand premia using separate hedonic regressions on each one of these data-sets. This methodology has the following two important advantages: First, it yields the maximum amount of flexibility since it does not impose any restrictions on how the parameters change across quarters and across processor types.[21] Second, by using the 486 brand premia as a control, it allows us to identify which changes in the relative brand premia in the Pentium product line are not associated with contemporaneous changes in brand premia in the 486 product line.[22]

Hedonic analysis does not typically suggest specific structural restrictions in functional form. Traditionally, a number of different specifications are used, with Box-Cox transformations being very prominent among them. We consider three of the most common specifications: (i) the linear model, (ii) the log-log model, (iii) Box-Cox transformations on the dependent variable. In

[20] There are no Pentium computers in the first three quarters. The number of Pentium computers in the fourth quarter is inadequate to perform a meaningful regression.

[21] We have also used finer partitions of the data-set. These suffer from smaller sample sizes and, therefore, yield higher standard errors. The qualitative results, thought, are generally the same.

[22] The use of the 486 brand premia as a control also allows us to account for changes in unobserved characteristics. A change in unobserved characteristics of a firm that affects pricing in both its Pentium and 486 line-up will not affect its *relative* Pentium price premium. Similarly, a change in an unobserved characteristic of all firms that affects the pricing of all Pentium or all 486 computers will not affect the firms' relative Pentium price premia.

addition, we consider a model for which component pricing is linear for any particular brand, but with multiplicative brand effects.

*3.1. Specifications.*

*(i) Linear Model.* The additive specification with the variables in levels preserves the additivity of component pricing across configurations. That is, doubling the size of a computer's hard drive should have the same effect on the price of a computer regardless of the size of its memory or its screen. Arguea and Hsiao (1993) show that when consumers can arbitrage away any differences between firms in component pricing and there is a continuum of products, the hedonic pricing rule will be linear in the components. We consider that the ability of consumers to arbitrage differences in component pricing is a plausible first order approximation in the personal computer industry since there exists a separate retail market for computer components. We later discuss the evidence on the existence of any arbitrage opportunities.

For each quarter and processor type, the hedonic regressions are of the form:

$$\begin{aligned} PRICE_i = {} & \sum_k a_k\, BRAND_{k,i} + b_1\, SPEED_i + b_2\, HARD_i + b_3\, RAM_i + \\ & d_1\, CD\text{-}ROM_i + d_2\, MULTI_i + d_3\, SCREEN15_i + d_4\, SCREEN17_i + e_i \end{aligned}$$

where $BRAND_{k,i}$ takes that value of 1 if computer i was advertized by $BRAND_k$ and zero otherwise, $SPEED_i$ is the clock speed of the processor, $HARD_i$ the size of the hard drive in MBs, $RAM_i$ the size of memory in MBs, $CD\text{-}ROM_i$ and $MULTI_i$ are dummies that indicate the inclusion of a CD-ROM and multi-media kit, respectively, and $SCREEN15_i$ and $SCREEN17_i$ are dummies that indicate whether the size of the monitor is respectively 15 or 17 inches.[23]

[23] Because we analyze the evolution of the *differences* in brand premia over time using the brand premia of the 486 line as a control, omitted variables would represent a problem only if their values changed differentially across firms *and* product lines over time.

*(ii) Log-Log Model.* The log-log specification is one of the most frequently used in the hedonic analysis of computer pricing.[24] Therefore, it is important to consider this specification as well in order to make our results directly comparable with those of the existing literature.

*(iii) Linear "Benchmark Computer" Pricing Model.* The linear specification imposes linearity with respect to both the brand dummies and the computer components. On the other hand, the log-log specification imposes a constant elasticity of price with respect to all the continuous variables and a multiplicative price effect for the dummy variables, including the brand effects. An intermediate specification is to preserve linearity with respect to computer components while allowing for multiplicative brand effects. This specification is motivated by the observation that doubling the size of the hard drive may have a different effect on price for different manufacturers. These differences may arise from differential component quality and, therefore, provide no arbitrage possibilities.

A specification which would preserve additivity with respect to all computer attributes but incorporate multiplicative brand effects is:

$$\begin{aligned} \text{PRICE}_i = \sum_k \alpha_k\,\text{BRAND}_{k,i}\,\big(&\beta_1\,\text{SPEED}_i + \beta_2\,\text{HARD}_i + \beta_3\,\text{RAM}_i + \\ &\delta_1\,\text{CD-ROM}_i + \delta_2\,\text{MULTI}_i + \delta_3\,\text{SCREEN15}_i + \delta_4\,\text{SCREEN17}_i\big) + \varepsilon_i \end{aligned}$$

where one of the brand coefficients is standardized to one to ensure identification.[25]

*(iv) Box-Cox Model.* Finally, we estimate the model using a Box-Cox transformation on the dependent variable:

$$\begin{aligned} \frac{\text{PRICE}_i^{\lambda} - 1}{\lambda} = \sum_k \alpha_k\,\text{BRAND}_{k,i} &+ \beta_1\,\text{SPEED}_i + \beta_2\,\text{HARD}_i + \beta_3\,\text{RAM}_i + \\ &\delta_1\,\text{CD-ROM}_i + \delta_2\,\text{MULTI}_i + \delta_3\,\text{SCREEN15}_i + \delta_4\,\text{SCREEN17}_i + \varepsilon_i \end{aligned}$$

---

[24] For some recent studies see Berndt and Griliches (1993), Berndt, Griliches, and Rappaport (1995), Cohen (1988), Lerner (1995), and Stavins (1995). Table 4.2 in Triplett (1989) summarizes the specifications used in older hedonic research on computers.

[25] We also consider a variation in which the error is multiplicative and obtain similar results.

The Box-Cox model nests the linear and log-linear models and provides us with a useful formal test of the linear model.[26]

*3.2. Estimation Methodology*.

Since the main focus of our study is the evolution of brand premia over time and their relationship with the entry sequence of firms and their reputation for quality, we average the estimates of the firm dummies for each of the following three groups: The early entrants group (AUSTIN and GATEWAY), the premium brands group (IBM and COMPAQ) which are also the latest entrants, and the "six pack" group (the six remaining firms).

Our measure of the idiosyncratic component of price dispersion, i.e., the price dispersion that is not due to the entry sequence of firms and their reputation for quality, is the within group variability of the price premia. Estimating the within group price variability would not have been possible if we had directly estimated the average brand premium for each of the three groups by using group instead of firm dummies. Nevertheless, the direct estimates of group premia are essentially the same as those obtained by averaging the estimates of the firm dummies.

Partitioning the data-set by processor type and quarter results in sample sizes (for the quarters used in the estimation) ranging from to a low of 126 observations to a high of 919. However, the number of observations of pentium computers that correspond to the two premium brands is relatively small for most quarters, ranging between 3 and 25. Nevertheless, the standard errors of the price premia of the premium brands are relatively small. The cell and sample size are listed in Table C-1 in Appendix C.

We estimated the linear specification with additive firm dummies with two different ways. First using OLS; second by using Weighted Least Squares, where the weights are the inverse of the number of observations in a particular model-observation.[27] As we noted in Section 2, the number of listed configurations for a particular model differs across firms. We want to make sure that our results are not driven by the few firms that have a large number of listed configurations

---

[26] For uses of the Box-Cox transformation in estimating hedonic models of computer prices and related discussion see Jorgenson and Landau (1989) and Triplett (1989).

[27] We estimated the non-linear model with OLS only.

for each of their models. Weighting the observations of these firms down is one way to verify the robustness of our results.[28]

A more formal way to do this is to adopt a random error components framework. We decompose the disturbance term as follows:

$$\epsilon_i = \zeta_j + \nu_i$$

where *i* is indexing the observations and *j* is indexing the model-observations. GLS estimation of this model follows Fuller and Battese (1973).[29] Though this methodology is essentially weighted least squares, the weights do not correspond to the ones we used except for the "average" observation and in the limit where the variance of $\nu_i$ goes to zero. The results are essentially the same for all three estimation procedures, which is not surprising given that OLS is consistent and our data-sets relatively large. Therefore, all other models are estimated using unweighted procedures.

*3.3. Discussion of the Linearity Assumption.*

All three of the continuous variables enter linearly in many of our specifications. We performed separate analyses that indicated, contrary to our initial expectations, that the linear form is actually a very good approximation. We collected separate data for the price of hard drives and RAM at four different months, spaced approximately a year apart from 1993 to 1996. These data came from the stand alone retail prices for these components as advertized by Insight Incorporated, MegaHaus, CDW and others. We plotted the prices versus the capacity of the memory chips and the hard drive. RAM prices are reasonably well described by a straight line from the origin. Hard drive prices are also well described by a straight line, which, however, has a positive intercept. This implies that our estimates of the hard drive coefficient in our hedonic regressions capture the incremental cost of hard drive capacity. Note that linearity in the stand alone price of hard drives and RAM does not necessarily imply linearity in the implied price for

[28] Yet another way by which we verified the robustness of our results was to estimate the set of regressions replacing the nine firm dummies by two group dummies corresponding to two of the three groups of firms.

[29] See also Hsiao (1986, p. 193-197), and Biorn (1981) for similar treatments.

these components when sold bundled with a personal computer. Firms may indeed, as we discussed in the introduction, price discriminate by having a price schedule that is nonlinear in the capacity of memory and the hard drive even if the cost of these components is actually linear. Nevertheless, our hedonic regression results indicate that the component prices are the same for both Pentium and 486 computers throughout the period. Furthermore, the bundled prices are almost always similar to the stand alone prices for these components. These results suggest that there is little price discrimination of this sort.[30]

The linearity with respect to the processor speed was even more surprising to us. We run separate regressions where the processor speed was controlled with a set of dummies for every processor. Even though the null hypothesis that the price effect processor speed is linear was rejected for most periods both for the Pentium and 486 processors, there was no systematic deviation from linearity, i.e., the pattern was neither convex nor concave. Since the coefficient of speed is a nuisance parameter, this finding indicates that imposing linearity with respect to processor speed is quite adequate.[31] Nevertheless, our findings are not sensitive to the linearity assumption: The log-log and Box-Cox models yield essentially identical results.

## 4. Estimation Results.

### *4.1. Relative Brand Premia.*

The nature of our estimation strategy yields a total of 20 regressions for each specification. Since the focus is on the coefficients of the brand dummies, we compute the group averages

$$\overline{PREMIUM}_{g,p,t} = \frac{1}{M_{g,p,t}} \sum_{b \in \boldsymbol{G}_g} PREMIUM_{b,p,t}$$

[30] This is most likely because, as we conjectured above, consumers can easily arbitrage between manufacturers and component vendors.

[31] The results with processor dummies had substantially higher standard errors compared to the results of the linear specification. There was no systematic differences in the coefficients between the two sets of regressions. For this reason we do not present these results. See Appendix B for details.

where $p$ indexes the processor type, $t$ indexes the quarter, $g$ indexes the group, $M_{g,p,t}$ is the number of brands in group $g$ that advertize computers of processor $p$ in quarter $t$, $\boldsymbol{G}_g$ is the set of brands in group $g$, and $PREMIUM_{b,p,t}$ is the estimate of the brand premium of firm $b$ for processor $p$ in quarter $t$.

In the tables below we report

$$\Delta\overline{PREMIUM}_{g,p,t} = \overline{PREMIUM}_{g,p,t} - \overline{PREMIUM}_{early\ entrants,p,t}$$

and

$$\sigma_{\Delta\overline{PREMIUM}_{g,p,t}} = Var\left[\frac{1}{M_{g,p,t}}\sum_{b \in \boldsymbol{G}_g} PREMIUM_{b,p,t} - \frac{1}{M_{g,p,t}}\sum_{b \in \boldsymbol{G}_{early\ entrants}} PREMIUM_{early\ entrants,p,t}\right]^{\frac{1}{2}}$$

for $g \in \{premium, six\ pack\}$ for all specifications. The remaining regression coefficients of the linear model are summarized in Figures 5 to 8 below, while those of the other models are omitted since they follow similar patterns.

Table 3 reports the results of the linear unweighted model. Two important points are to be made with regards to the results for the 486-based models: (i) The “6 pack” firms command no price premium relative to the early entrants. Their group average premium is significantly different than those of the early entrants in only 3 quarters, and in only one of these the difference is positive. The absolute value of the difference in the brand premia exceeds $100 only in one quarter. One should also note that during the introduction of the Pentium, the two groups do not have a significant difference in their premia. (ii) The two premium firms have premia that average about $400 higher than the other two groups. Except for an increase of the IBM’s prices in the middle of the sample period, this difference has been broadly stable throughout the period. This picture is markedly different for the Pentium based computers. The group of the 6 latter entrants has prices approximately $400 higher than those of the early entrants at the time of entry. This average declines in the second quarter to about half its original size, but remains significant. By the third quarter the two groups of firms have similar pricing patterns, as they also do for their 486 models. This pattern is even more pronounced for our two premium firms, which constitute

the latest entrants. At the time of introduction they command a price premium over the early entrants of a whopping $2,000. This falls steadily over time, and after a year and a half their price premium is, at around $400, similar to that of their 486 line-up. These results are further highlighted in Figures 2 and 3.[32] The weighted and error components regressions yield a similar pattern. The only difference between the two sets of results is that the weighted regression estimates have somewhat smaller standard errors. Finally, similar results are obtained if, instead of using the by group average of the firm brand dummies, we directly estimate a linear model with group dummies. The error component results are reported in Table C-2 in the Appendix, while the others are omitted.[33]

The most commonly used log-log specification also yields results, shown in Table 4, that are qualitatively identical to those of the linear model. However, the log-log model does not predict price as well as the linear model. For both models we computed the ratio of the explained variance of price to the total variance of price

$$r^2 = \frac{s^2_{P\hat{R}ICE - \overline{PRICE}}}{s^2_{PRICE - \overline{PRICE}}}$$

for each quarter.[34] The fit of the linear model, as measured by $r^2$, is better than that of the log-log model for all but one quarter for Pentium computers and one quarter for 486 computers.

The results of the specification with linear pricing within a brand and multiplicative brand effects are broadly similar with those of the linear and log-log specifications. The estimates pertaining to the firm dummies and their standard deviation are reported in Table C-3 and Figures C-1 and C-2. The reported coefficients for each group are the differences of that group's average brand premium and the average brand premium of the early entrants, which is normalized to 1.

---

[32] The error bars in these and all remaining figures correspond to the 95% confidence interval.

[33] Because the results are robust to estimation technique, the results of regressions with weighted observations, error-component regressions, and regressions with group instead of firm dummies were not repeated for most of the remaining specifications.

[34] For the linear model, this is equal to the $R^2$ of the regression.

The estimated premia of this model are nearly equal to those of the log-log specification.[35] This suggests that the estimates of the proportional relative brand premia are not sensitive to the functional form of component pricing: In the former model price is equal to the product of characteristics and brand dummies, while in the latter model price is a linear function of characteristics. Finally, the fit of this and the linear model is similar as measured by the estimated variance of the disturbance term, with the non-linear model having a slight, but consistent across quarters, edge for 486 computers.

We finally turn to the estimation results of the Box-Cox model. Box-Cox estimation provided us with the following dilemma: Should we estimate a single value of λ for all quarters or should we estimate a different value of λ for each quarter ? We decided to estimate a single value of λ for each of the two processor types since this allows parameter estimates to be comparable across quarters. For each of the two processor types we computed the value of λ that maximized the joint likelihood function for all quarters:

$$\hat{\lambda} = \arg\max_{\lambda} \left\{ \sum_{q} \ln(L_q(\lambda)) \right\}$$

where

$$\ln(L_q(\lambda)) = k - \frac{N_q}{2} \ln(\hat{\sigma}_q^2) + (\lambda - 1) \sum_{i_q=1}^{N_q} \ln PRICE_i$$

is the concentrated log-likelihood for quarter $q$, *conditional* on the value of λ, $N_q$ is the number of observations in quarter $q$, $k$ is a constant, and $\hat{\sigma}_q^2$ is the estimated variance of the equation disturbance term. [See Spitzer (1982) for details.] The estimated value of λ for the 486 computers is equal to 0.59 and for the Pentium computers it is equal to 0.77. Even though λ is closer to 1 than to zero, the null hypothesis of λ=1 is rejected for both product lines at any reasonable level of significance. This is not surprising given the large sample size. The results, however, are

[35] The estimates for the two models, even though not directly comparable, are nearly comparable, since the first order Taylor's expansion of $e^x$ around zero is 1 + x.

qualitatively the same with those of all previous specifications and are, therefore, relegated to Table C-4 in Appendix C.

*4.2. Discussion.*

The following stylized facts emerge from the analysis presented above: (i) Non-premium firms that market Pentium computers relatively late charge the same prices for their 486 line-ups compared to the other non-premium firms, (ii) Non-premium firms that market Pentium computers relatively late *initially* charge *higher* prices for their Pentium line-ups compared to the other non-premium firms, (iii) The price premium of high reputation firms for 486 computers is relatively stable throughout this period, (iv) The price premium of these firms for Pentium computers is initially much higher than that for 486 computers but declines to that same level over the course of 1½ years.

The stylized facts (i) and (ii) suggest that otherwise identical firms which introduce a product later command a temporary price premium in the market. This is consistent with the presence of loyal customers who are willing to wait and even pay a price premium in order to purchase computers from these firms. For any order of firm entry in Pentium market, the early entrants will be able to sell both to their loyal consumers and to 'swing' consumers, that is, consumers that are not loyal to any brand. When the second wave of entrants introduces their models, the consumers who have not bought a personal computer consist disproportionately from consumers that are loyal to these firms. The optimal strategy of these firms is to capture rents from these consumers by posting a price that is higher than that of the early entrants. As this 'overhang' of loyal consumers purchases computers and exits the pool of prospective buyers, the late entrants find it optimal to compete for less loyal consumers, and therefore, reduce their prices relative to the early entrants. In the long run, the relative prices of firms will be determined by the steady state distribution of loyal and 'swing' consumers and their willingness to pay for different brands. A stylized example that captures the intuition described above is presented in Appendix A.

Stylized facts (iii) and (iv) indicate a decline in the "price" of quality as the new technology matures. This can be attributed either to a decline in the consumer willingness to pay for quality,[36] or to consumer perceptions of a progressively declining quality gap, or to both. However, high quality firms are also amongst those who market Pentium computers relatively late. Therefore, part of the decline in their price premium could be attributed to the presence of consumers with brand loyalty, as discussed in the preceding paragraph. In fact these two ideas are complementary: It is the highest quality firms that are expected to have the most loyal consumers. This would explain the very high premia that these firms charge in the first year since their entry.

Alternatively, the high relative Pentium prices charged by premium brands could be driven by their desire to avoid "cannibalizing" their own 486 sales. Cannibalization is a bigger concern for these firms as their Pentium product lines compete more directly with their own 486 product lines. This is because (a) products of other firms are not as close substitutes with products of premium firms and (b) products of non-premium firms are close substitutes with each other.[37] Another type of "cannibalization" that is relevant to premium firms but not for others is the competition of Buy Direct sales with those from other channels. Firms for which resellers and retailers are important can not charge a lower price in the direct market than retailers charge in the retail market. This suggests that premium firms may advertise in the Buy Direct press to get customers who search only that way, but charge retail level prices. This is also consistent with the much lower advertising intensity of these firms.

Finally, the high initial prices charged by the high quality firms might have been due to a miscalculation, from their part, of the consumer willingness to pay for their products. These firms reduced their prices as sales proved to be unsatisfactory.[38] In order to provide support or eliminate this "hybris" hypothesis one would need to estimate the demand for each firm's products in this oligopolistic setting *without* imposing the assumption of optimal pricing. This is a tall order

---

[36] This can be driven by a change in the composition of consumers over the product cycle. Early consumers are primarily those who purchase frontier products and are, therefore, more quality sensitive.

[37] See Bresnahan, Stern, and Trajtenberg (1997).

[38] In fact, Compaq and IBM were soon to follow more aggressive marketing strategies, aiming at the home, as opposed to only the business, market.

**Table 3.** Estimation results, linear model, unweighted observations. Average brand premia by group relative to early entrants.

| | 486 Models | | | | | | Pentium Models | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6 Pack | | Premium Brands | | $R^2$ | N | 6 Pack | | Premium Brands | | $R^2$ | N |
| Quarter | Estimate | Standard Error | Estimate | Standard Error | | | Estimate | Standard Error | Estimate | Standard Error | | |
| 93 I | 86.2 | 47.8 | 210.7 | 106.7 | 0.8719 | 289 | | | | | | |
| 93 II | 141.3 | 45.6 | 394.4 | 70.0 | 0.8379 | 423 | | | | | | |
| 93 III | -41.4 | 29.7 | 470.5 | 41.9 | 0.8636 | 793 | | | | | | |
| 93 IV | -31.0 | 25.8 | 469.5 | 33.0 | 0.8907 | 817 | | | | | | |
| 94 I | -22.6 | 35.0 | 402.6 | 45.3 | 0.8937 | 775 | 307.1 | 102.7 | | | 0.8901 | 126 |
| 94 II | -45.7 | 33.3 | 478.9 | 40.9 | 0.8914 | 919 | 170.8 | 42.2 | 2098.5 | 79.9 | 0.9467 | 402 |
| 94 III | -87.5 | 26.3 | 680.0 | 37.6 | 0.9245 | 678 | 12.5 | 26.4 | 1284.0 | 106.9 | 0.9541 | 508 |
| 94 IV | -35.4 | 29.2 | 568.0 | 48.2 | 0.9043 | 535 | 59.9 | 25.2 | 1219.5 | 90.8 | 0.9620 | 466 |
| 95 I | -62.2 | 23.4 | 559.0 | 52.6 | 0.9097 | 473 | 63.5 | 26.2 | 1309.5 | 89.0 | 0.9247 | 666 |
| 95 II | 2.6 | 27.7 | 377.0 | 40.4 | 0.9498 | 336 | 64.5 | 33.3 | 762.5 | 110.6 | 0.9022 | 690 |
| 95 III | 9.9 | 52.7 | 399.5 | 82.2 | 0.9401 | 143 | -19.0 | 30.3 | 571.5 | 88.8 | 0.9371 | 678 |
| 95 IV | | | | | | | 4.3 | 23.9 | 328.5 | 39.7 | 0.9594 | 634 |

NOTE: Only three firms were advertizing Pentium computers in 1993. We therefore, omit these results. Similarly, we do not report the results for 486 computers for the last quarter of 1995, as only ZEOS and COMPAQ were advertizing 486-based models during this period. Premium brands start advertizing Pentium based computers in the second quarter of 1994.

[redacted]

**Table 4.** Estimation results, log-log model. Average brand premia by group relative to early entrants.

| Quarter | 486 Models | | | | | | Pentium Models | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6 Pack | | Premium Brands | | $R^2$ | N | 6 Pack | | Premium Brands | | $R^2$ | N |
| | Estimate | Standard Error | Estimate | Standard Error | | | Estimate | Standard Error | Estimate | Standard Error | | |
| 93 I | 0.065 | 0.020 | 0.129 | 0.047 | 0.8608 | 289 | | | | | | |
| 93 II | 0.090 | 0.017 | 0.216 | 0.026 | 0.8762 | 423 | | | | | | |
| 93 III | 0.037 | 0.012 | 0.271 | 0.017 | 0.8742 | 793 | | | | | | |
| 93 IV | 0.068 | 0.012 | 0.307 | 0.015 | 0.8763 | 817 | | | | | | |
| 94 I | 0.041 | 0.017 | 0.239 | 0.023 | 0.8776 | 775 | 0.050 | 0.020 | | | 0.9182 | 126 |
| 94 II | 0.008 | 0.016 | 0.256 | 0.020 | 0.8792 | 919 | 0.065 | 0.013 | 0.548 | 0.028 | 0.9086 | 402 |
| 94 III | -0.008 | 0.013 | 0.353 | 0.019 | 0.9061 | 678 | 0.021 | 0.031 | 0.370 | 0.039 | 0.9211 | 508 |
| 94 IV | 0.005 | 0.015 | 0.307 | 0.025 | 0.8903 | 535 | 0.011 | 0.010 | 0.319 | 0.036 | 0.9329 | 466 |
| 95 I | -0.001 | | | | | | | | | | | |

and requires, at a miminum, high frequency data of deliveries by firm and market segment. This data was not readily available.

*4.3. Idiosyncratic Price Dispersion.*

We define the idiosyncratic component of price dispersion as the standard deviation of the brand premia around the group means:

$$\sigma_{p,t} = \left[ \frac{1}{M_{p,t} - 3} \sum_{b=1}^{M_{p,t}} \left( PREMIUM_{b,p,t} - \overline{PREMIUM}_{g,p,t} \right)^2 \right]^{\frac{1}{2}}$$

where $PREMIUM_{b,p,t}$ is the estimated premium for a particular brand for processor $p$ in quarter $t$, $\overline{PREMIUM}_{g,p,t}$ is average premium for the group that this brand belongs to for processor $p$ in quarter $t$, and $M_{p,t}$ is the number of brands advertizing computers with processor $p$ in quarter $t$. This is our measure of the impact of all other factors, such as differences in the firms' perceptions of the market environment and their production capabilities, on price dispersion. Figure 4 plots the idiosyncratic component of price dispersion using the results of the linear model.

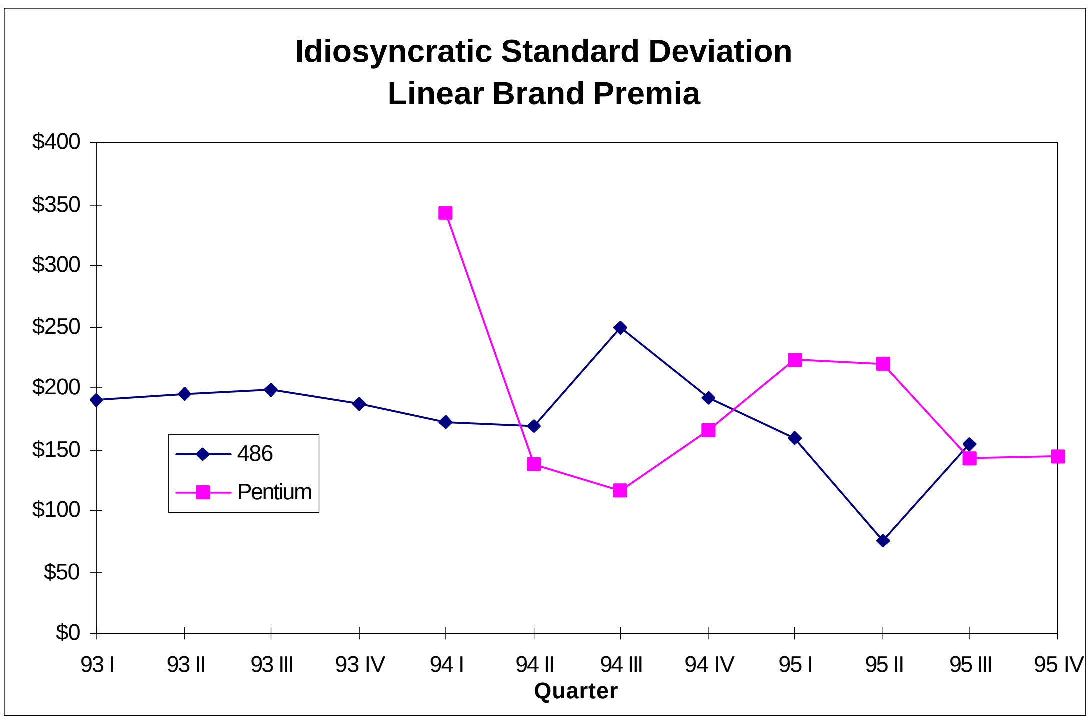



Figure 4

The idiosyncratic component shows no trend over the sample period. However, its variance increases for both 486 and Pentium based computers after the introduction of the latter.[39]

*4.4. Testing for Price Discrimination.*

We finally examine the possibility that manufacturers are able to price discriminate by differentially pricing computer components across computers. Figures 5 through 8 summarize the estimates of component prices for the linear model. These estimates are similar to those obtained from the weighted regressions and qualitatively similar to those obtained from the non-linear specifications. The price of RAM and 17 inch monitors is almost identical for both product lines.[40] One could argue that the price of hard drives is different for 486 than for Pentium computers, starting out lower in the first quarter while being higher in the second year.[41] Since hard drive differentials are not so easy to arbitrage since every computer comes with one and adding a hard drive takes up a bay and is more tedious than adding RAM, it makes sense that any pricing differences are more likely to occur in hard drive pricing than in that of other components. One might use a similar argument to explain why the incremental price of 15 inch monitors, though usually not significantly different for the two line-ups, is less similar than the incremental price of 17 inch monitors.[42]

A formal joint test of the equality of the component coefficients between Pentium and 486 based computers for all time periods would reject the equality of these coefficients. But requiring equality of these coefficients for all quarters is probably not reasonable. There will naturally be some variations in the pricing of these components over time. In fact, close examination of the results indicates that for some quarters a particular component commands a higher price for

---

[39] This result is robust to specification.

[40] In fact, the incremental price of RAM is almost identical to that in the secondary market.

[41] The stand alone incremental price of hard drives falls in between the bundled price for the Pentium and 486 computers. However, the price of stand alone hard drives was much lower in 1993 compared to the implied price for the hard drives bundled in 486 computers (there were no Pentiums at the time). Arbitrage did not seem to be very effective in that time period.

[42] We do not consider differences in the price of multimedia packages as there is probably substantial differences in their quality.

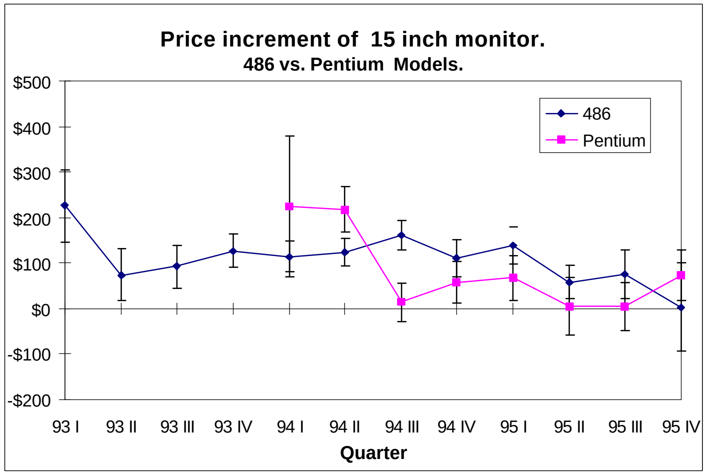



Figure 5

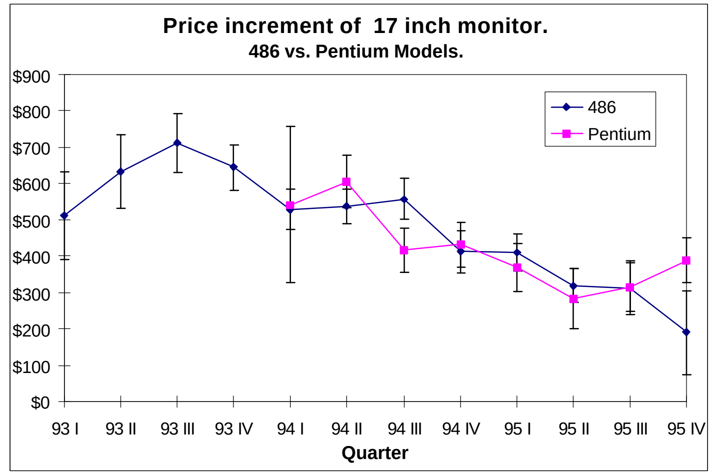



Figure 6

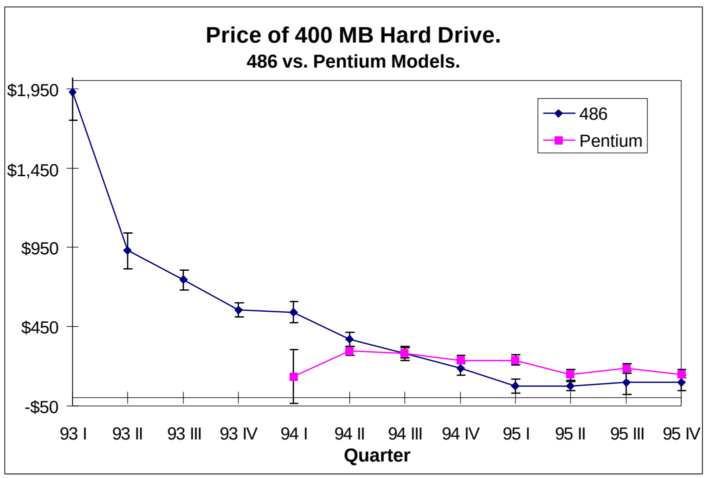



Figure 7

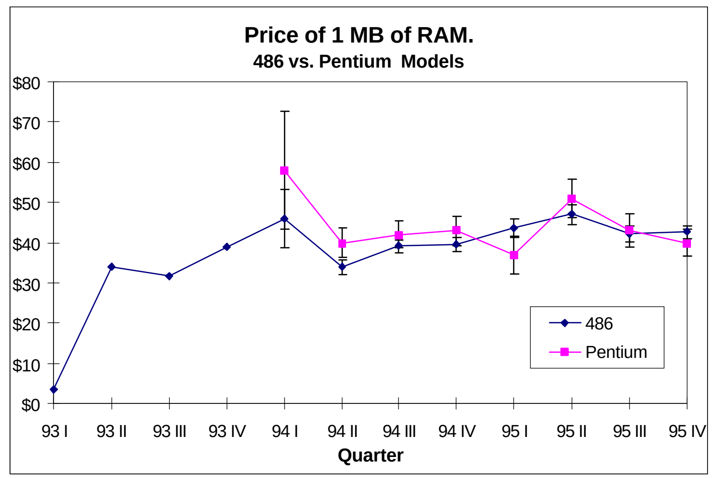



Figure 8

Results of Linear Model. Error bars correspond to 95% confidence intervals.

Pentium relative to 486 computers while for a later quarter it commands a lower price. A more reasonable approach is to view the component coefficients as draws from a joint density. For instance, the coefficient of the marginal price of RAM for Pentium computers in period *t* could be written as:

$$\hat{\beta}_{RAM,\ Pentium,\ t} = \beta_{RAM,\ Pentium,\ t} + \tilde{\epsilon}_{RAM,\ Pentium,\ t}$$

where

$$\beta_{RAM,\ Pentium,\ t} = \gamma_{RAM,\ Pentium} + \tilde{u}_{RAM,\ Pentium,\ t}$$

and $\tilde{\epsilon}_{RAM,\ Pentium,\ t}$ represents sampling error, the standard deviation of which is equal to the standard error of $\hat{\beta}_{RAM,\ Pentium,\ t}$, and $\tilde{u}_{RAM,\ Pentium,\ t}$ is a normally distributed random variable. We then test for the equality of $\gamma_{RAM,\ Pentium}$ and $\gamma_{RAM,\ 486}$ approximating the distribution of $\tilde{\epsilon}_{RAM,\ Pentium,\ t}$ by a normal distribution.[43]

The methodology of formally testing the null hypothesis of no systematic price discrimination is presented in Appendix D. Using the estimates of the linear and non-linear unweighted models, we fail to reject the null hypothesis for all four components. The test results are shown in Tables D-1 and D-2.

## 5. Matched Model Analysis.

An alternative way to look at the evolution of relative firm prices over time is to identify particular models for which we have repeated observations for a number of periods and firms. Using this method we can compute the brand premia directly, without having to control for any differences in computer characteristics. However, most advertized configurations differ across firms and change over time for any particular firm. Thus, only a very small number of observations can be used, resulting in relatively "noisy" estimates of price differences. Nevertheless, matched model analysis provides a "reality-check" about the plausibility of the price differences estimated by the regression results. Obtaining this "second reading" is particularly important given the rather

[43] This approximation is not a poor one given the amount of observations in each of our samples.

large estimated price differences between the premium and non-premium brands reported in the preceding section.

A frequently advertized configuration for 486 computers includes a 33 MHz processor, 4 MB of RAM, a hard drive between 200 and 240 MB, no CD-ROM, a 14 inch monitor, and 1 MB of graphics memory. For every quarter and every firm we computed the average advertized price of the models with these specifications.[44] These where then used to compute the average price for each one of the three firm groups. Figure 9 below plots the differences of the prices of the "early entrants" from those of the premium and '6-pack' firms. This figure parallels and is directly comparable with Figure 2 above. For the most part a similar (but more accentuated) pattern holds: Firms that are first to advertize the pentium based computers have higher prices for 486 based computers, compared to the other non-premium firms, for the first half of 1993. The price difference disappears by the time the Pentium computers are introduced. However, unlike the regression results, the price of the premium firms decline to the level of the non-premium firms by the time this model is discontinued.

The most frequently advertized configuration for Pentium computers includes a 60 MHz processor, 8 MB of RAM, a hard drive between 450 and 500 MB, a 14 inch monitor, and 1 MB of graphics memory. There were are about 50 quotes of models with these specifications. We constructed the group price differences, as above. The results are plotted in Figure 10. Due to the small number of price quotes, we could only compare group prices for three quarters.[45] Though it is hard to draw general conclusions from such a brief period,[46] prices of both "6-pack" and premium firms are shown to decline relative to those of the early entrants. Again, the results are the same as those obtained from the regression analysis, but even more pronounced: The price differences between the three groups are bigger than the ones shown in Figure 3 above.

---

[44] There are about 150 such quotes.

[45] In fact, we interpolated the price for the premium group for the last two quarters of 1994 from quotes in the two adjacent quarters.

[46] In particular, since the first two quarters of 1994 is not included.

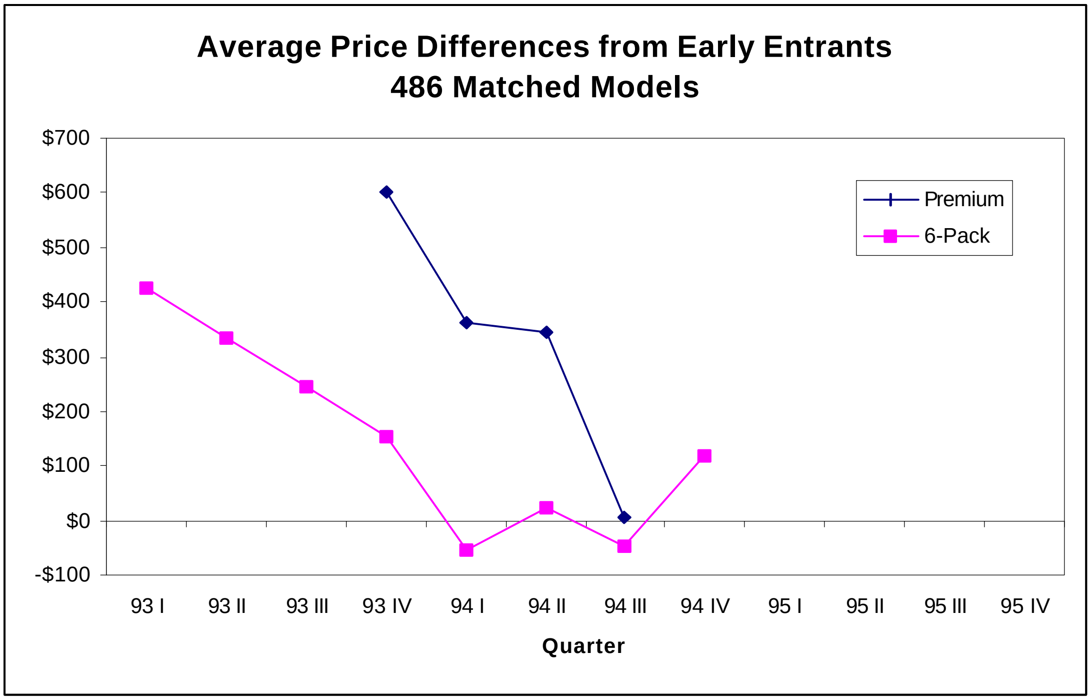



Figure 9

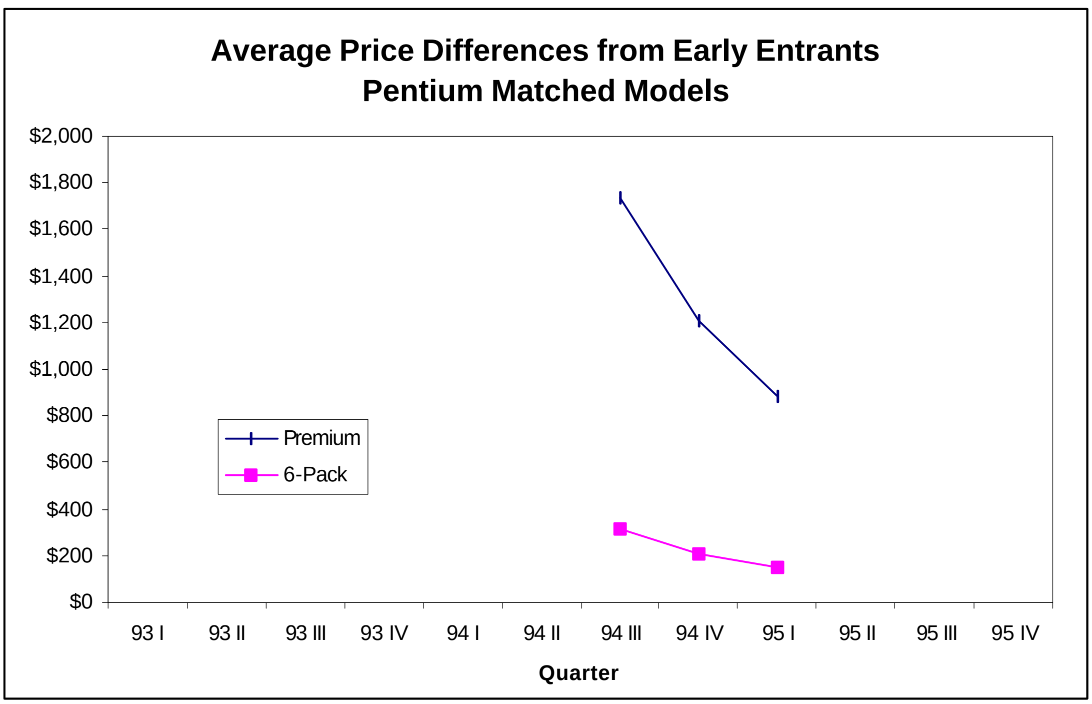



Figure 10

## 6. Conclusion.

The transition from 486 to Pentium based personal computers provides us with an opportunity to study the effects of entry order on firm pricing. In the personal computer industry, the technology the firms are moving from, and the technology they are moving to, are exogenous to the industry itself and dictated by the Intel processors. Furthermore, the computer manufacturers have limited ability to price discriminate by pricing computer components differentially for the 486 and Pentium product lines. Therefore, the task of evaluating the effect of entry order on firm pricing is somewhat easier.

We find that early entrants employ a less aggressive pricing strategy than late entrants. These price differences diminish as the Pentium market matures. We also find that the price premium for quality declines rapidly over the product cycle. These results suggest that brand loyalty is important in this market, willingness to pay for quality declines as the composition of consumers changes over the product cycle, and, brand coefficients in hedonic models can not be interpreted as capturing unobserved quality only.

**APPENDIX A. A Simple Model of Pricing under Sequential Entry.**

Later entrants would initially charge higher prices than early entrants if consumers have a certain degree of brand loyalty, that is, (i) they are willing to pay a premium to purchase a product of their liking, and (ii) they are willing to wait until the brand of their choice introduces a computer.

In this Appendix, we analyze a very stylized two period duopoly model in which firms enter sequentially into a market. The order of entry is exogenous, that is, one of the two firms does not have the option to enter early, perhaps because it is slower in developing its version of the product.[47] Consumers are characterized by a varying degree of loyalty to either of the two firms. We show that the second entrant in the market will charge a higher price than the first entrant in the market.

Denote the two firms by A and B. There is a continuum of consumers located on the unit interval. The per period utility that a consumer with location $x$ derives from purchasing the product of firm A is $U_A(x) = V - x$. The per period utility he derives from purchasing from firm B is $U_B(x) = V - (1-x)$. [48] Consumers with low values of $x$ have a relatively high willingness to pay for the product of firm A and a low willingness to pay for the product of firm B. Conversely, consumers with high values of $x$ have high willingness to pay for the product of firm B and a low willingness to pay for the product of firm A.

We consider a sub-game perfect equilibrium in which some consumers purchase from firm A in period 1, and in which the two firms compete for customers in period 2. This is the "interesting case" and we show that this equilibrium exists for $V > 6/5$.[49] For simplicity we also assume that

---

[47] We show that if one of the two firms has the option to enter early, it will choose to do so.

[48] These preferences correspond to those of a market with horizontally differentiated products where the two firms are located at the endpoints of the product space. This specification implies that strong preference for one brand results in strong aversion to the other brand. The model could be extended to allow for high willingness to pay for both brands by allowing V to differ across consumers.

[49] For $V<5/6$, the two firms do not directly compete with each other in period 2: they are monopolists on their side of the unit interval. For $5/6<V<6/5$ all consumers purchase a product from one of the two firms.

the marginal cost of both firms is equal to zero. In Period 1, Firm A offers its product and charges a price $P^A_1$. Consumers with strong preference for the product of firm A will purchase from that firm in period 1. Suppose these consumers have location $x < x_1$ . In Period 2, Firm B introduces its own product and the two firms choose prices simultaneously. Denote the second period prices by $P^A_2$ and $P^B_2$.

The profit function of firm B is given by

$$\Pi_2^B = P_2^B(1 - x_c)$$

where

$$x_c = \frac{1 + P_2^B - P_2^A}{2}$$

is the location of the critical consumer who is indifferent between purchasing from either firm. The First Order Condition of profit maximization with respect to $P^B_2$ yields

$$P_2^B = \frac{P_2^A + 1}{2}$$

Similarly, the profit function of firm A is

$$\begin{aligned}\Pi_2^A &= P_2^A(x_c - x_1)\\ &= P_2^A\left(\frac{1 + P_2^B - P_2^A}{2} - x_1\right)\end{aligned}$$

The First Order Condition of profit maximization with respect to $P^A_2$ yields

$$-P_2^A + \frac{1 + P_2^B}{2} - x_1 = 0$$

Substituting for the optimal response of firm B and solving for $P^A_2$ yields the equilibrium in 2nd period prices

However, the consumer who is indifferent between the two firms is also indifferent between purchasing and not purchasing at all. A multiplicity of 2nd period equilibria exists for this range of V.

$$P_2^A = 1 - \frac{4}{3}x_1$$

$$P_2^B = 1 - \frac{2}{3}x_1$$

Observe, next, that the consumer who is located at $x_1$ is indifferent between purchasing from firm A in period 1 or waiting to purchase the product of firm A in period 2. That is,

$$2(V - x_1) - P_1^A = V - x_1 - P_2^A \quad \Rightarrow$$

$$x_1 = V - P_1^A + P_2^A$$

Firm A chooses its price in period 1 to maximize its profits over both periods.

$$\Pi^A = P_1^A x_1(P_1^A) + P_2^A(P_1^A)[x_c(P_1^A) - x_1(P_1^A)]$$

Substituting from above, taking the First Order Condition with respect to $P_1^A$, and solving for $P_1^A$ yields

$$P_1^A = \frac{5}{26}V + \frac{33}{26}$$

In deriving this equilibrium we have implicitly assumed that

(i) u($x_c$) > 0 and

(ii) $0 < x_1 < x_c < 1$.

These inequalities are satisfied for 6/5 < V < 5/2. Furthermore, for this range of V, all prices are positive.[50]

It is straightforward to check that (i) $P_1^A > P_2^B$. for V > - 5/11 and that (ii) $P_2^B > P_2^A$ for V > 1/3. Therefore, for all values of V high enough to yield competition between the two firms, the period 1 price of the early entrant is higher than the period 2 price of the late entrant, which in turn is higher than the period 2 price of the early entrant. These price behavior is consistent with the empirical results of this paper.

[50] For V > 5/2 firm A chooses to produce only in the first period, while firm B sells to the remaining consumers in the second period. For sufficiently high V, firm B is pushed off the market all together and firm A sells to all consumers in period 1.

**APPENDIX B. Analysis Using Dummy Variables for Processor Speed.**

In our specifications, we impose a linear relationship between the clock speed of the processor and the price of the computer. One might suspect that this relationship is non-linear, especially at the high end, where the incremental price of a MHz might be higher than that for the lower speed processors. In order to explore the quality of the linear approximation, we repeated our regressions replacing the processor clock speed with processor dummies. We refer to this second set of regressions as the unconstrained regressions, because no constraint is imposed in the relationship between the processor clock speed and the computer price.

The average, over all quarters, incremental cost one MHz of clock speed is shown in Table B-1 below. Even though we reject the null hypothesis that the coefficients of the processor dummies fall on a line, we see that there is no systematic increase or decrease in the incremental price of clock speed. The two unusual estimates are the high incremental cost from the 25 to 33 MHz processors, and the negative incremental cost of moving from the 66 to 75 MHz Pentium processors. The negative estimates for the incremental cost of the 75 MHz Pentium processor are associated with large standard errors.

**Table B-1.** Quarter Average of Incremental Cost of 1 MHz of Clock Speed.

| | | | | 486 Processors | Pentium Processors |
|---|---|---|---|---|---|
| From | 25 | To | 33 MHz | 51.2 | |
| | 33 | | 50 MHz | 8.9 | |
| | 50 | | 66 MHz | 8.9 | |
| | 60 | | 66 MHz | | 22.6 |
| | 66 | | 75 MHz | 8.7 | -10.4 |
| | 75 | | 90 MHz | | 14.5[b] |
| | 75 | | 100 MHz | 5.7[a] | |
| | 90 | | 100 MHz | | 24.9 |
| | 100 | | 120 MHz | | 12.8 |
| | 120 | | 133 MHz | | 17.0 |

NOTES: (a) In one quarter the change is from 66 to 100 MHz. (b) In two quarters the change is from 66 to 90 MHz.

Due to the lack of any apparent increasing or decreasing returns to clock speed we believe that imposing a linear relationship between clock speed and the price of a computer will not bias our estimates for the coefficients of interest. This was confirmed by comparing a portion of the results of the unconstrained and the constrained regressions. The two sets of results were not systematically different. However, the unconstrained results had much higher standard errors. For this reason, in our paper we present the results obtained from the constrained regressions.

**APPENDIX C.** Cell and Sample Sizes, Error Components, Log-Log, and Box-Cox Results.

**Table C-1.** Cell and Sample Sizes.

| | 486 | | | | Pentium | | | |
|---|---|---|---|---|---|---|---|---|
| Quarter | 6-Pack | Early Entrants | Premium Brands | Total | 6-Pack | Early Entrants | Premium Brands | Total |
| 93 I | 215 | 68 | 6 | 289 | | | | |
| 93 II | 363 | 43 | 17 | 423 | | | | |
| 93 III | 635 | 99 | 59 | 793 | | | | |
| 93 IV | 563 | 126 | 128 | 817 | | | | |
| 94 I | 557 | 73 | 145 | 775 | 103 | 23 | | 126 |
| 94 II | 722 | 60 | 137 | 919 | 361 | 35 | 6 | 402 |
| 94 III | 561 | 58 | 59 | 678 | 445 | 60 | 3 | 508 |
| 94 IV | 406 | 109 | 20 | 535 | 389 | 73 | 4 | 466 |
| 95 I | 392 | 60 | 21 | 473 | 574 | 86 | 6 | 666 |
| 95 II | 296 | 25 | 15 | 336 | 600 | 82 | 8 | 690 |
| 95 III | 130 | 10 | 3 | 143 | 591 | 79 | 8 | 678 |
| 95 IV | | | | | 518 | 91 | 25 | 634 |

**Table C-2.** Error-components estimation results, linear model. Average brand premia by group relative to early entrants.

| | 486 Models | | | | Pentium Models | | | |
|---|---|---|---|---|---|---|---|---|
| | 6 Pack | | Premium Brands | | 6 Pack | | Premium Brands | |
| Quarter | Estimate | Standard Error | Estimate | Standard Error | Estimate | Standard Error | Estimate | Standard Error |
| 93 I | 181.4 | 66.6 | 335.8 | 133.0 | | | | |
| 93 II | 165.9 | 77.0 | 412.1 | 102.6 | | | | |
| 93 III | 19.4 | 65.0 | 531.9 | 79.8 | | | | |
| 93 IV | 54.0 | 57.2 | 612.0 | 71.3 | | | | |
| 94 I | 44.5 | 55.0 | 471.9 | 69.8 | 307.7 | 102.9 | | |
| 94 II | 14.9 | 61.7 | 541.2 | 79.7 | 166.9 | 55.2 | 2097.7 | 108.5 |
| 94 III | -70.5 | 74.0 | 696.9 | 86.8 | -7.1 | 46.9 | 1287.3 | 134.7 |
| 94 IV | 38.3 | 65.8 | 598.6 | 82.5 | 6.7 | 53.9 | 1156.3 | 110.9 |
| 95 I | 0.7 | 56.3 | 622.1 | 86.6 | 64.7 | 65.7 | 1321.6 | 143.9 |
| 95 II | 37.5 | 50.0 | 411.3 | 62.7 | 68.8 | 45.8 | 724.7 | 125.5 |
| 95 III | 34.7 | 78.3 | 418.2 | 108.2 | -24.5 | 43.2 | 574.3 | 98.1 |
| 95 IV | | | | | 11.8 | 37.1 | 343.4 | 41.7 |

NOTE: Only three firms were advertizing Pentium computers in 1993. We therefore, omit these results. Similarly, we do not report the results for 486 computers for the last quarter of 1995, as only ZEOS and COMPAQ were advertizing 486-based models during this period. Premium brands start advertizing Pentium based computers in the second quarter of 1994.

**Table C-3.** Estimation results, non-linear model, unweighted observations. Average brand premia by group relative to early entrants.

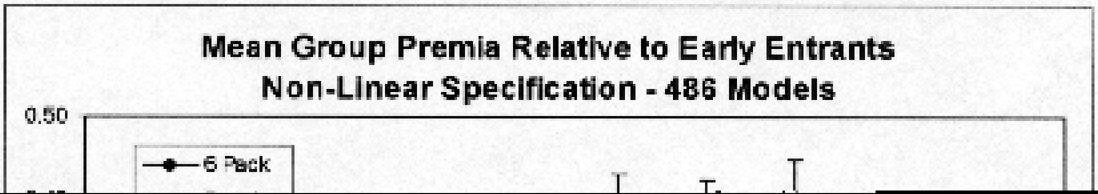
| | 486 Models | | | | Pentium Models | | | |
|---|---|---|---|---|---|---|---|---|
| | 6 Pack | | Premium Brands | | 6 Pack | | Premium Brands | |
| Quarter | Estimate | Standard Error | Estimate | Standard Error | Estimate | Standard Error | Estimate | Standard Error |
| 93 I | 0.065 | 0.017 | 0.142 | 0.053 | | | | |
| 93 II | 0.062 | 0.019 | 0.192 | 0.032 | | | | |
| 93 III | -0.005 | 0.012 | 0.246 | 0.019 | | | | |
| 93 IV | 0.018 | 0.010 | 0.275 | 0.016 | | | | |
| 94 I | 0.041 | 0.016 | 0.237 | 0.025 | 0.075 | 0.026 | | |
| 94 II | 0.011 | 0.019 | 0.305 | 0.020 | 0.052 | 0.013 | 0.682 | 0.028 |
| 94 III | -0.002 | 0.012 | 0.392 | 0.020 | 0.003 | 0.009 | 0.490 | 0.042 |
| 94 IV | 0.023 | 0.013 | 0.371 | 0.027 | 0.024 | 0.009 | 0.477 | 0.037 |
| 95 I | -0.004 | 0.011 | 0.382 | 0.033 | 0.024 | 0.010 | 0.605 | 0.044 |
| 95 II | 0.025 | 0.015 | 0.253 | 0.025 | 0.026 | 0.012 | 0.354 | 0.056 |
| 95 III | 0.010 | 0.029 | 0.261 | 0.050 | -0.013 | 0.011 | 0.258 | 0.043 |
| 95 IV | | | | | -0.001 | 0.009 | 0.127 | 0.016 |

NOTE: Only three firms were advertizing Pentium computers in 1993. We therefore, omit these results. Similarly, we do not report the results for 486 computers for the last quarter of 1995, as only ZEOS and COMPAQ were advertizing 486-based models during this period. Premium brands start advertizing Pentium based computers in the second quarter of 1994.

**Table C-4.** Estimation results, Box-Cox model. Average brand premia by group relative to early entrants.

| | 486 Models [λ=0.59] | | | | Pentium Models [λ=0.77] | | | |
|---|---|---|---|---|---|---|---|---|
| | 6 Pack | | Premium Brands | | 6 Pack | | Premium Brands | |
| Quarter | Estimate | Standard Error | Estimate | Standard Error | Estimate | Standard Error | Estimate | Standard Error |
| 93 I | 7.654 | 4.351 | 11.627 | 1.949 | | | | |
| 93 II | 7.526 | 1.871 | 11.435 | 2.872 | | | | |
| 93 III | 1.216 | 1.182 | 22.267 | 1.666 | | | | |
| 93 IV | 3.094 | 1.077 | 24.107 | 1.373 | | | | |
| 94 I | 2.287 | 1.502 | 20.792 | 1.943 | 48.062 | 15.654 | | |
| 94 II | 0.364 | 1.429 | 22.904 | 1.755 | 26.733 | 6.565 | 318.181 | 12.430 |
| 94 III | -0.600 | 1.119 | 31.560 | 1.599 | 2.439 | 2.252 | 206.109 | 17.134 |
| 94 IV | 1.955 | 1.250 | 28.498 | 2.060 | 11.538 | 4.032 | 205.692 | 14.469 |
| 95 I | -0.372 | 1.038 | 28.578 | 2.032 | 11.448 | 4.233 | 219.774 | 14.311 |
| 95 II | 1.916 | 1.243 | 19.914 | 1.809 | 8.758 | 5.254 | 121.837 | 17.397 |
| 95 III | 1.444 | 2.385 | 20.468 | 3.718 | -4.565 | 4.827 | 92.559 | 14.130 |
| 95 IV | | | | | 1.125 | 3.867 | 56.824 | 6.409 |

NOTE: Standard errors are *conditional* on λ. Only three firms were advertizing Pentium computers in 1993. We therefore, omit these results. Similarly, we do not report the results for 486 computers for the last quarter of 1995, as only ZEOS and COMPAQ were advertizing 486-based models during this period. Premium brands start advertizing Pentium based computers in the second quarter of 1994.


Mean Group Premia Relative to Early Entrants
Non-Linear Specification - 486 Models
0.50
6 Pack

[redacted]

**APPENDIX D. Testing the Assumption of no Systematic Price Discrimination.**

As we discussed in the main body of the paper, testing equality of component coefficients between Pentium and 486 computers for all periods is too strong of a test: Even small, random, month to month variations in component prices for both product lines will result in a rejection of the null hypothesis. What we are really interested in is the possibility that long run systematic differences in component prices exist between the two platforms. A reasonable approach for testing this hypothesis is to view the component *coefficients* (as opposed to only the coefficient estimates) as draws from a joint density. For example, the coefficient of the marginal price of a component for Pentium computers in period *t* could be written as:

$$\hat{\beta}_{Pent,t} = \beta_{Pent,t} + \tilde{\epsilon}_{Pent,t}$$

where $\beta_{Pent,t} = \gamma_{Pent} + \tilde{u}_{Pent,t}$ , $\tilde{\epsilon}_{Pent,t}$ is sampling error (the std. deviation of the regression coefficient), and $\tilde{u}_{Pent,t}$ is a normally distributed random variable.

Similarly, the coefficient of the marginal price of a component for 486 computers in period *t* could be written as:

$$\hat{\beta}_{486,t} = \beta_{486,t} + \tilde{\epsilon}_{486,t}$$

where $\beta_{486,t} = \gamma_{486} + \tilde{u}_{486,t}$ , $\tilde{\epsilon}_{486,i}$ is sampling error, and $\tilde{u}_{486,t}$ is a normally distributed random error.

We are going to devise a procedure to test the equality of $\gamma_{486}$ and $\gamma_{\text{Pent}}$. Approximating the distribution of $\tilde{\epsilon}_{Pent,t}$ by a normal distribution we have: [51]

$$\begin{bmatrix} \hat{\beta}_{486,t} \\ \hat{\beta}_{Pent,t} \end{bmatrix} \sim N\left( \begin{bmatrix} \gamma_{486} \\ \gamma_{Pent} \end{bmatrix}, \begin{bmatrix} \sigma^2_{\epsilon_{486,t}} + \sigma^2_{u_{486}} & \sigma_{u_{486},\, u_{Pent}} \\ \sigma_{u_{486},\, u_{Pent}} & \sigma^2_{\epsilon_{Pent,t}} + \sigma^2_{u_{Pent}} \end{bmatrix} \right)$$

[51] It is actually t-distributed with N-K degrees of freedom.

Then, the variance of the average coefficient of the component price of, say, 486 computers is:

$$\sigma^2_{\bar{\hat{\beta}}_{486,t}} = \frac{1}{T^2} \sum_{t=1}^{T} \sigma^2_{\hat{\beta}_{486,t}}$$

$$= \frac{1}{T^2} \sum_{t=1}^{T} \sigma^2_{\epsilon_{486,t}} + \frac{1}{T} \sigma^2_{u_{486}}$$

We estimate $\sigma^2_{\hat{\beta}_{486,t}}$ by $\left(\hat{\beta}_{486,t} - \bar{\hat{\beta}}_{486,-t}\right)^2$, where $\bar{\hat{\beta}}_{486,-t}$ is the average coefficient estimate excluding the estimate for period t. An estimate of $\sigma^2_{u_{486}}$ is:

$$\hat{\sigma}^2_{u_{486}} = \frac{1}{T} \sum_{t=1}^{T} \left(\hat{\beta}_{486,t} - \bar{\hat{\beta}}_{486,-t}\right)^2 - \frac{1}{T} \sum_{t=1}^{T} \sigma^2_{\epsilon_{486,t}}$$

and similarly for $\hat{\sigma}^2_{u_{Pent}}$.

An estimate for $\sigma_{u_{486},\, u_{Pent}}$ is: [52]

$$\hat{\sigma}_{u_{486},\, u_{Pent}} = \frac{1}{T-1} \sum_{t=1}^{T} \left(\hat{\beta}_{486,t} - \bar{\hat{\beta}}_{486,t}\right)\left(\hat{\beta}_{Pent,t} - \bar{\hat{\beta}}_{Pent,t}\right)$$

Observe that under the null hypothesis, the difference between the Pentium and 486 component coefficients for any period *t* is distributed

$$\left(\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}\right) \sim N\left(0, \sigma^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}}\right)$$

where

$$\sigma^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}} = \sigma^2_{\epsilon_{486,t}} + \sigma^2_{u_{486}} + \sigma^2_{\epsilon_{Pent,t}} + \sigma^2_{u_{Pent}} - 2\ \sigma_{u_{486},\, u_{Pent}}$$

The difference between the two coefficients for period *t* is assumed to be independent from that of another period. Therefore:

---

[52] We allow the covariance to be positive, as components of Pentium and 486 computers will in general have common price shocks.

$$\overline{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}} \sim N\left(0, \frac{1}{T^2} \sum_{t=1}^{T} \sigma^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}}\right)$$

The above analysis suggests the test statistic:

$$\tau = \frac{\overline{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}}}{\frac{1}{T}\sqrt{\sum_{t=1}^{T} \hat{\sigma}^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}}}}$$

where

$$\hat{\sigma}^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}} = \sigma^2_{\epsilon_{486,t}} + \hat{\sigma}^2_{u_{486}} + \sigma^2_{\epsilon_{Pent,t}} + \hat{\sigma}^2_{u_{Pent}} - 2\ \hat{\sigma}_{u_{486},\ u_{Pent}}$$

The results of this test-statistic are shown in Table D-1 below. The reported p-values are based on the normal distribution, and are, therefore, conservative for small samples since the variance of the difference is estimated. That is, if we fail to reject equality with normal p-values, we would also fail to reject equality using the small distribution of $\tau$.

**Table D-1.** Tests for Systematic Price Differences in Component Prices.

| | Linear Model | | Non-Linear Model | |
|---|---|---|---|---|
| Component | Test Statistic | p-value | Test Statistic | p-value |
| 15 inch Monitor | 0.70 | 0.482 | 1.33 | 0.185 |
| 17 inch Monitor | 0.48 | 0.634 | 0.72 | 0.473 |
| Hard Drive | 0.19 | 0.848 | 0.17 | 0.864 |
| RAM | -1.28 | 0.201 | -1.22 | 0.222 |

Note: All results are based on unweighted regressions.

The results presented above show that we fail to reject the null of no-systematic differences in component prices between the 486 and Pentium product lines.

The testing procedure outlined above does not take into consideration the fact that the component parameters are estimated with varying degrees of precision in different quarters. By appropriately weighting the difference of the estimates for each period, we can obtain a lower variance estimate of the average difference in the component prices.

The variance weighted test statistic is

$$\tau_w = \frac{\sum_{t=1}^{T} w_t \left(\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}\right)}{\sqrt{\sum_{t=1}^{T} w_t^2 \; \hat{\sigma}^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}}}}$$

where

$$w_t = \frac{1}{\sigma^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}}} \left( \sum_{p=1}^{T} \frac{1}{\sigma^2_{\hat{\beta}_{486,p} - \hat{\beta}_{Pent,p}}} \right)^{-1}$$

$$\hat{\sigma}^2_{\hat{\beta}_{486,t} - \hat{\beta}_{Pent,t}} = \sigma^2_{\epsilon_{486,t}} + \hat{\sigma}^2_{u_{486}} + \sigma^2_{\epsilon_{Pent,t}} + \hat{\sigma}^2_{u_{Pent}} - 2\,\hat{\sigma}_{u_{486},\,u_{Pent}}$$

The value of the precision-weighted test statistic for the four components we examine is given is Table D-2 below. The results are similar to those obtained from the unweighted test statistic.

**Table D-2.** Tests for Systematic Price Differences in Component Prices.

| | Linear Model | | Non-Linear Model | |
|---|---|---|---|---|
| Component | Test Statistic | p-value | Test Statistic | p-value |
| 15 inch Monitor | 0.89 | 0.372 | 1.50 | 0.134 |
| 17 inch Monitor | 0.61 | 0.543 | 0.83 | 0.406 |
| Hard Drive | 0.08 | 0.939 | 0.07 | 0.943 |
| RAM | -1.05 | 0.295 | -1.00 | 0.316 |

Note: All results are based on unweighted regressions and precision-weighted test-statistic.

**REFERENCES.**


ARGUEA, Nestor M. and Cheng HSIAO [1993], "Econometric Issues of Estimating Hedonic Price Functions: With an Application to the US Market for Automobiles," *Journal of Econometrics*, vol. 56, pages 243-267.

BAGNOLI, Mark, Stephen W. SALANT, and Joseph E. SWIERZBINSKI [1989], "Durable-Goods Monopoly with Discrete Demand," *Journal of Political Economy*, volume 97, pages 1459-1478.

BIORN, Erik [1981], "Estimating Economic Relations from Incomplete Cross Section/Time Series Data," *Journal of Econometrics*, volume 16, pages 221-236.

BERNDT, Ernst and Zvi GRILICHES [1993] "Price Indexes for Microcomputers: An Exploratory Study," in M. E. Manser, M. F. Foss, and A. H. Young (eds.), *Price Measurements and their Uses*, NBER Studies in Income and Wealth 57 (Chicago: University of Chicago Press, 1993), pages 63-93.

BERNDT, Ernst, Zvi GRILICHES, and Neal J. RAPPAPORT [1995] "Econometric Estimates of Price Indexes for Personal Computers in the 1990's," *Journal of Econometrics*, volume 68, pages 243-268.

BRESNAHAN, Timothy, Scott STERN, and Manuel TRAJTENBERG [1997] "Market Segmentation and the Sources of Rents from Innovation: Personal Computers in the Late 1980s," *RAND Journal of Economics*, volume 28, pages S17-S44.

COASE, Ronald [1972] "Durable Goods Monopolists," *Journal of Law and Economics*, volume 15, pages 143-150.

COHEN, Jonathan M. [1988] "Rapid Change in the Personal Computer Market: A Quality-Adjusted Hedonic Price Index, 1976-1987," unpublished S.M. Thesis, MIT, Alfred P. Sloan School of Management.

ELIASHBERG, Jehoshua and Abel P. JEULAND [1986] "The impact of Competitive Entry in a Developing Market Upon Dynamic Pricing Strategies," *Marketing Science*, volume 5, pages 20-36.

FULLER, Wayne A. and George E. BATTESE [1973] “Transformations for estimation of linear models with nested-error structure,” *Journal of the American Statistical Association*,” volume 68, pages 626-632.

HOGAN, Mike [1994] “First PCI-Pentiums: AST, DELL, and IBM.” *PC/Computing*, January 1994, volume 7, pages 36-37.

HSIAO, Cheng [1986] *Analysis of Panel Data*, Cambridge University Press, Cambridge, U.K.

JORGENSON, Dale W. and Ralph LANDAU, editors [1989] *Technology and Capital Formation*, MIT Press, Cambridge, MA.

KAHN, Charles [1986] “The Durable Goods Monopolist and Consistency with Increasing Costs,” *Econometrica*, pages 275-294.

LERNER, Josh [1995] “Pricing and Financial Resources: An Analysis of the Disk Drive Industry, 1980-88,” *Review of Economics and Statistics*, volume 77, pages 585-598.

*PC Magazine*, January 1993 to December 1995, Ziff-Davis Publishing Company.

*PC World*, June 1994, PC World Communications, Inc.

SPITZER, John J. [1982] “A Primer on Box-Cox Estimation,” *Review of Economics and Statistics*, volume 64, pages 307-313.

STAVINS, Joanna [1995] “Model Entry and Exit in a Differentiated-Product Industry: The Personal Computer Market,” ” *Review of Economics and Statistics*, volume 77, pages 571-584.

STOCKEY, Nancy L. [1979] “Inter-temporal Price Discrimination,” *Quarterly Journal of Economics*, volume 93, pages 355-371.

TRIPLETT, Jack E. [1989] “Price and Technological Change in a Capital Good: A Survey of Research on Computers,” in Jorgenson and Landau, editors, *Technology and Capital Formation*, MIT Press.