Measuring Consumer Welfare in the CPU Market.

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Abstract

The personal computer Central Processing Unit (CPU) has undergone a dramatic improvement in quality, accompanied by an equally remarkable drop in prices in the 1990s. How have these developments in the CPU market affected consumer welfare? This paper estimates demand for CPUs and measures consumer welfare. The model is based on a quasilinear utility function with one random variable. The model does not have the idiosyncratic logit error term, so that consumer welfare directly reflects consumers' valuation of product characteristics. Welfare calculations show that consumer surplus makes up approximately 90% of the total social surplus and that a large part of the welfare gains comes from the introduction of new products. Similar results are found when the model is extended to include two random coefficients without the idiosyncratic logit error term - the pure characteristics demand model. Simulation results show how "quality competition" among firms can generate a large gap between the reservation and actual prices.

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1 Introduction

The past decade has seen a dramatic improvement in performance of the personal computer Central Processing Unit (CPU).[1] Rapid advances in manufacturing technology have allowed a new generation of products to emerge every two to three years. The most well-known of the CPUs, the Intel-made Pentium, was introduced in 1993 with 60 megahertz (Mhz) processing speed. Five new generations of processors have entered the market since then, with the Pentium III processor reaching 1 gigahertz (Ghz) processing speed in 2000.

While performance continued to improve over the 1990s, the average price of CPUs fell. The first Pentium processor was introduced at $878 but the Pentium II processor, faster than the Pentium processor by a factor of four, was marketed at $636 four years later. Figure 1 shows the maximum and quantity-weighted average prices of CPUs with maximum processor speed (in Mhz) from 1993 to 2000. It is clear that despite frequent introductions of new products with higher speed, the average price shows a downward trend. The figure also shows that the maximum price does not increase much, although the rate of new product introduction goes up sharply from 1998 on.

On the one hand, consumers benefit from the drastic improvement in product quality, accompanied by price decline. Moreover, since the computer is the main driving force behind the boom of the information technology industry, its economic importance is not confined to the CPU industry. However, on the other hand, a high turnover in products incurs a considerable cost. Since the first mover gains transitory market power, firms are engaged in an "innovation race"

[1] Since CPU is the microprocessor assembled with the motherboard, I will use the two terms interchangeably in this paper.

which requires a few billion dollars for R&D activities and capital expenditures every quarter.[2] The Semiconductor Industry Association reports that R&D expenditures have grown at an annual rate of 15 % over the last decade, and that the ratio of R&D spending to sales reached 13.8% in 1999, which surpasses other high technology industries.[3] Capital expenditures have also grown at an annual rate of over 15% over the same period, and the ratio of capital expenditures to sales fluctuates between 15% and 20%.[4]

Do benefits to consumers exceed the cost of innovation and firms' profits? This paper attempts to answer this question by estimating consumer welfare using the product level data of two major firms in the CPU market: Intel and Advanced Micro Devices (AMD). The data set provides quarterly data on prices and quantities sold from 1993 to 2000. Welfare gains from innovation have been studied in other industries. For example, Petrin (2002) estimates welfare gains from the development of the Minivan in the auto industry. Hausman (1997) examines the impact of regulatory delay in the introduction of the cell phone on consumer surplus. Nevo (*forthcoming*) estimates consumer benefit from new brand introductions in the ready-to-eat cereal market. This paper, however, investigates a series of innovations in one of the most innovative industries. This temporal perspective enables me to explore the effects of changes in the rate of innovation on consumer welfare, in addition to measuring welfare gains from innovation.

Measuring consumer welfare requires that I estimate demand. I use characteristic space instead of product space following the discrete choice literature. Although the CPU is one of the

[2] Another cost stems from product obsolescence. Products exit the market, not because they are physically obsolete, but because firms want to avoid cannibalization among their own products.

[3] The pharmaceutical industry spends 11% of sales on R&D activities, the optical instruments industry spends 9%, the communication industry spends 8%, and the aircraft industry spends 4%.

[4] Total R&D and capital expenditures by U.S. merchant semiconductor firms exceeded $20 billion in 1999.

most complex manufactured products, only a few of its attributes are adequate to project it onto the characteristic space. One attribute is processing speed, the main attribute of the CPU. That indicates how fast it processes commands. Another attribute is whether it has a level 2 (L2) cache inside. The L2 cache is a data storage device which speeds up tasks by storing data inside the CPU during computation. A CPU without the L2 cache has to "communicate" with a separate memory device outside the CPU, and this slows down computational time. Both Intel and AMD produce two types of CPUs, one with the L2 cache and one without.[5]

I construct a demand model following Bresnahan(1987) and Berry(1994). The utility function of consumers is quasilinear with one random variable but without an idiosyncratic error term, the so called logit error term. This model is often called the vertical model.[6] Most of the recent empirical industrial organization literature relies on the multinomial logit demand model to estimate demand and to measure consumer welfare.[7] The logit demand model facilitates the estimation by insuring that all the purchase probabilities are nonzero at every value of the parameter vector, and that the market share equation has smooth derivatives. However, Petrin (2002) shows that in the multinomial logit model a large part of welfare changes are generated by the idiosyncratic error term.[8] Until the error term is interacted with demographic data, the model implies misleadingly that consumers strongly dislike characteristics of products they buy relative to their alternative choices. This problem is no longer present in the vertical model so that consumer welfare directly reflects consumers' valuation of product characteristics.

[5] See the next section for details.

[6] "Vertical differentiation" is defined as follows: given any two distinct products, *if they were sold at the same price*, then *all* consumers would choose the same one (the "higher quality" product). (Shaked and Sutton, 1987)

[7] See McFadden (1981) , Berry, Levinsohn and Pakes (1995) , Nevo (2001) , and Petrin (2002) .

[8] The logit error term is often intepreted as tastes for products which are independent of product characteristics and across consumers. For more detailed exposition on this issue, see Berry and Pakes (2002).

Another motivation for using the vertical model is that it imposes a substitution pattern that describes the market with vertically differentiated products. In the vertical model, only products in the adjacent "neighborhood" are substitutes for each other, while the logit demand model treats all products as substitutes for one another. For example, if the price of the 400 Mhz CPU goes up, the vertical model predicts that some consumers will switch to the 350 Mhz or the 450 Mhz CPU, while the logit demand model predicts that consumers will switch to all other CPUs in the market. Although these two patterns are two extreme cases, the substitution pattern imposed by the vertical model better describes the CPU market.

Later in the paper, I extend the vertical model to include another random coefficient. The extended model is called the pure characteristics demand model (Berry and Pakes, 2002), and the vertical model is a special case.[9] The pure characteristics model does not require that consumers agree on the ranking of products as they do in the vertical model, and this results in a more flexible substitution pattern. At the same time, the absence of the idiosyncratic error term still guarantees that consumer welfare directly reflects consumers' valuation of product characteristics. Nevertheless, there has been no application of this model, since an estimation strategy has not been available. However, Berry and Pakes (2002) have recently provided an estimation strategy, and my paper is the first that estimates the model with real data.

Consumer welfare, calculated based on parameter estimates from these models, shows that consumer surplus surpasses producer surplus, measured by the variable profit, as well as firms' R&D spending. Consumer welfare is calculated in two ways in order to deal with changes in the value of

[9] In this paper the pure characteristics model refers to the model which has multiple random coefficients without the idiosyncratic error term.

the outside option over time. In the first way, I assume that the value of the outside option does not change over time, and all welfare changes come from products in the sample. In the second way, I identify the value of the outside option from the time dummy variables, based on a reasonable assumption. Although there is a considerable difference in the level of consumer welfare, results of both approaches suggest that consumer welfare increases when the rate of innovation goes up, and that consumers gain far more than firms.

A closer look at consumer welfare reveals that a large part of welfare gains comes from the introduction of new products. For example, in the first quarter of 2000, consumers who bought new Pentium III 1 Ghz CPUs were willing to pay $5,700 more than what they paid. This suggests that firms do not fully extract reservation value at the high end of the market. I run simulations to show how "quality competition" among firms can generate a large gap between the reservation price and the actual price. The simulation results suggest that the price does not necessarily increase with quality improvements if a rival firm catches up by improving its own product quality.

The rest of the paper is organized as follows. Section 2 provides an industry description with details of the data set. Section 3 explains the construction of the demand model. Section 4 outlines the estimation strategy and Section 5 reports estimation results. Section 6 measures consumer welfare and Section 7 extends the model to have two random coefficients. Section 8 examines effects of quality competition on prices using simulations. Section 9 concludes and discusses extensions.

2 Industry and Data

2.1 Industry Description

The history of the personal computer CPU dates back to 1974 when the Intel-made 8080 microprocessor became the brain of the first personal computer–the Altair, allegedly named for a destination of the Starship *Enterprise* from the *Star Trek* television show. Then in 1978 IBM chose the Intel 8088 CPU as the brain of the IBM PC, and Intel became one of the fastest growing firms in the seventies, thanks to the success of the IBM PC in the PC market. Although the dominance of the IBM PC ended in the late 1980s with a surge of other firms into the market, Intel continued to prosper by supplying its products to new entrants.

The rivalry between Intel and Advanced Micro Devices (AMD) started in the nineties. In 1991 AMD introduced the AM386 microprocessor family, breaking the Intel monopoly. After Intel introduced the Pentium-class processor in 1993, AMD increased its market share by targeting consumers at the low end of the market. 486 users who did not want to ditch their 486-based PCs yet welcomed the AMD 5x86 CPU, which was designed to offer Pentium-class performance while operating on a standard 486 motherboard. Cyrix was another major player at the low end of the market, and its 5x86 CPU was considered the only real competition to the AMD counterpart.

During the sample period, *i.e.* from 1993 to 2000, Intel's market share generally fluctuated between 75% and 85%. It gained considerable market share during 1996 and 1997 on the strength of its Pentium/MMX processor. On the other hand, AMD, which had 15% of the market share in the early 1990s, started losing it in 1996, as demand for the older-generation 486 collapsed. Its market share went down to 5% in 1997, as it was late to introduce its Pentium-class K5 processor.

However, in 1998 Intel lost 14% of market share partly due to the success of AMD's K6 series processors and partly due to its failure to deliver strong products at the low end of the market. Intel quickly recovered its market share up to 82% in 1999 with the success of the Celeron processor, the low end version of the Pentium-class CPU.[10] Since 1998 AMD's market share has been steadily increasing, reaching almost 15% in 2000, but Cyrix's market share suffered due to its inability to deliver faster speed processors.

In the late 1990s, there were two significant changes in the CPU market. First, Intel started tackling the low end of the market with Celeron-class processors. Before the introduction of the Celeron processor, Intel had targeted these consumers with the previous generation product, and it was not as competent as its rivals at the low end of the market. However, thanks to the success of the Celeron CPU, Intel increased its market share. Second, in 1998 the semiconductor industry switched from a 3 year product cycle to a 2 year product cycle. This means that the industry moved to the next generation of the manufacturing technology every two years instead of every three years. As a result, the rate of the new product introduction went up.

These two changes have shortened the lifespan of the CPU from 10∼12 quarters to 4∼6 quarters. The more frequent introduction of the new generation of products, combined with the provision of new products for the low end of the market, forces existing products to exit the market sooner than before. These changes provide an opportunity to explore the effects of changes in the rate of innovation on consumer welfare.

[10] The Celeron is a stripped down version of the Pentium-class CPU with the level-2 (L2) cache removed. Later Intel added 128 kilobytes of the L2 cache on the Celeron board, but its capacity is still a quarter of the L2 cache on the Pentium II board.

2.2 Data

The data set consists of quarterly data on price, units sold and product characteristics of Intel and AMD products.[11] The sample period starts at the second quarter of 1993 when Intel first introduced Pentium processors and ends at the third quarter of 2000. However, I treat 386 and 486 class processors as the outside option since price data on these chips are not available. The 486 chip was a mainstream product until the first quarter of 1995, accounting for more than 60% of all Intel products. Then its share dropped to 5% in the first quarter of 1996, and it exited the market in the second quarter of 1996. This leaves me with 55 CPUs. I treat the world CPU market at different quarters as different markets, and this gives me 30 markets with 320 observations in total.

Table 1 shows summary statistics of the data set. During the sample period, the semiconductor industry has succeeded in developing five generations of lithography technology (the second column). The lithography technology determines how many transistors can be put on the processor. The more transistors the processor has, the faster and the better it becomes. Since the lithography technology provides the processor with a range of speeds, processor speed and lithography technology are closely correlated. However, the lithography technology is a generic technology. What distinguishes products among different brands is an actual pattern of transistors inscribed on the wafer. So although Intel and AMD use the same photolithography technology, they produce different products by drawing different patterns of transistors on the wafer.

When Intel made the first Pentium chip in 1993, it used 0.8 micron lithography technology

[11] I have acquired data on price and quantity from MicroDesign Resources (MDR). MDR is an independent research group that collects data and provides analysis on the microprocessor market. However, data on AMD products are not as well classified as those on Intel products. Only average price and quantity on groups of products are available.

which allowed 3.1 million transistors to be incorporated on a single chip. In 2000, 0.18 micron technology became the mainstream, allowing 20 million transistors to operate on a single chip. With advances in lithography technology the processor speed went up from 60 Mhz in 1993 to 1 Ghz in 2000.

In estimating demand I use two specifications to allow a more flexible relationship between processor speed and product quality. In one specification I use processor speed and processor speed squared, and in another, I use processor speed and dummy variables for lithography technology.

Another characteristic, not shown in the table, is the level-2 (L2) cache. Both Intel and AMD produce a CPU without the L2 cache.[12] The L2 cache is an extra memory storage inside the processor which stores data during computation. Having the memory storage inside the processor enables the processor to speed up computation by reducing a communication time between the processor and the main memory chip outside the processor. So even if two processors have the same speed and employ the same technology, there is a significant difference in their performance depending on whether they have the L2 cache or not. However, since the manufacturing cost goes down without the L2 cache, there is a large discrepancy in price between processors with and without the L2 cache.

The average price of a CPU has declined slightly since 1996. The average price is higher before 1996 because it does not reflect the price decline of 386 and 486 CPUs. The maximum price fluctuates despite the drastic improvement in process performance. As shown in Figure 1, the more frequent introduction of new products in the late 1990s caused only a moderate increase in the maximum price of CPUs.

[12] Intel names it Celeron and AMD names it Duron.

While the average price decreases slightly, prices of individual products drop drastically. For example, the price of a Pentium II 333 Mhz processor dropped to \$275 from \$738 in one year. The price of a Pentium III 500 Mhz processor dropped to \$173 from \$696 in one and a half years. Figure 2 shows time paths of four different CPUs introduced at different points of time. Despite a performance improvement over time, they all follow a very similar price trend.

3 Demand Model

Suppose there are $t = 1, 2, ..., T$ markets, each with $i = 1, 2, ..., I_t$ consumers. A market is defined as the world CPU market at a certain quarter. Given a market, the indirect utility of consumer i from product j is

$$
\begin{aligned}
u_{ij} &= \delta_j - \alpha_i p_j, \quad \text{for } 1 \leq j \leq J \\
u_{i0} &= \delta_0 \qquad (1)
\end{aligned}
$$

where δ_j is the quality of product j, p_j is the price of product j, and α_i is the individual-specific coefficient.[13] $j = 0$ represents the outside option and I assume p_0 is zero. The outside option is to buy non Intel and AMD products, and u_{i0} represents the utility of buying neither Intel nor AMD products.

Now put products in the order of ascending price. A rational consumer i decides to purchase

[13] See Appendix I for how to derive the indirect utility function from the consumer utility maximization.

product j if and only if $u_{ij} > u_{ik}$, $\forall k \neq j$.[14] This is equivalent to

$$\delta_j - \alpha_i p_j > \delta_k - a_i p_k, \quad \forall k \neq j \tag{2}$$

which implies

$$\alpha_i < \frac{\delta_j - \delta_k}{p_j - p_k}, \quad \text{if} \;\; p_j > p_k \tag{3a}$$

$$\alpha_i > \frac{\delta_k - \delta_j}{p_k - p_j}, \quad \text{if} \;\; p_k > p_j \tag{3b}$$

for all $k \neq j$.The utility maximizing consumers with α_i will buy product j if and only if

$$\begin{aligned} \alpha_i &< \min_{k<j} \frac{\delta_j - \delta_k}{p_j - p_k} = \overline{\triangle}_j (\delta, p) \quad \text{and} \\ \alpha_i &> \max_{k>j} \frac{\delta_k - \delta_j}{p_k - p_j} = \underline{\triangle}_j (\delta, p) . \end{aligned} \tag{4}$$

Letting $\overline{\triangle}_0 (\delta, p) = \infty$ and $\underline{\triangle}_J (\delta, p) = 0$, I have the market share equation for product j as

$$s_j (\boldsymbol{\delta}, \mathbf{p}; \Omega, F) = \left(F \left(\overline{\triangle}_j (\delta, p) | \boldsymbol{\theta} \right) - F \left(\underline{\triangle}_j (\delta, p) | \boldsymbol{\theta} \right) \right) 1 \left\{ \overline{\triangle}_j > \underline{\triangle}_j \right\}, \quad \text{for } j = 0, ..., J, \tag{5}$$

where $1 \left\{ \overline{\triangle}_j > \underline{\triangle}_j \right\}$ is an indicator function that gives 1 if $\overline{\triangle}_j > \underline{\triangle}_j$ and 0 otherwise and Ω is a vector of all unknown parameters. $F(\alpha_i|\boldsymbol{\theta})$ represents the cumulative distribution function of α_i with density $f(\alpha|\boldsymbol{\theta}) = dF(\alpha|\boldsymbol{\theta})/d\alpha$, where $\boldsymbol{\theta}$ is a vector of parameters of the distribution. Since the distribution of α represents the consumer's heterogeneous valuation on the product quality, I

[14] If $u_{ij} = u_{ik}$, a consumer is indifferent between two products.

assume $F(\alpha|\boldsymbol{\theta})$ has positive support. And for analytic convenience, I also assume that both $F(\alpha|\boldsymbol{\theta})$ and $f(\alpha|\boldsymbol{\theta})$ are continuous.

Proposition 1 *Suppose there are rational consumers and J number of products in the market. Then every product has a positive market share if and only if* $\min_{k<j} \frac{\delta_j-\delta_k}{p_j-p_k} > \max_{k>j} \frac{\delta_k-\delta_j}{p_k-p_j}$, $\max_{k>j} \frac{\delta_k-\delta_j}{p_k-p_j} = \frac{\delta_{j+1}-\delta_j}{p_{j+1}-p_j}$ *and* $\min_{k<j} \frac{\delta_j-\delta_k}{p_j-p_k} = \frac{\delta_j-\delta_{j-1}}{p_j-p_{j-1}}$.

Proof. *see Appendix for proof.* ■

The proposition implies that in order for all products to have positive market shares, it should hold

$$\frac{\delta_J-\delta_{J-1}}{p_J-p_{J-1}} < ... < \frac{\delta_3-\delta_2}{p_3-p_2} < \frac{\delta_2-\delta_1}{p_2-p_1} < \frac{\delta_1}{p_1}. \tag{6}$$

and that the market share of product j is

$$s_1(\boldsymbol{\delta}, \mathbf{p}; \Omega, F) = F\left(\frac{\delta_1}{p_1}|\boldsymbol{\theta}\right) - F\left(\frac{\delta_2-\delta_1}{p_2-p_1}|\boldsymbol{\theta}\right), \tag{7a}$$

$$s_j(\boldsymbol{\delta}, \mathbf{p}; \Omega, F) = F\left(\frac{\delta_j-\delta_{j-1}}{p_j-p_{j-1}}|\boldsymbol{\theta}\right) - F\left(\frac{\delta_{j+1}-\delta_j}{p_{j+1}-p_j}|\boldsymbol{\theta}\right), \quad \text{for } 1<j<J \tag{7b}$$

$$s_J(\boldsymbol{\delta}, \mathbf{p}; \Omega, F) = F\left(\frac{\delta_J-\delta_{J-1}}{p_J-p_{J-1}}|\boldsymbol{\theta}\right) \tag{7c}$$

Figure 3 shows the market shares for products $j-1$, j, and $j+1$ with the corresponding cutoff points under the gamma distribution. It is worth noting that the cutoff point is the ratio of the quality difference to the price difference between two adjacent goods. In other words, what determines the market share of product j is how far product j is located from its neighbor products in terms of the price-adjusted quality difference rather than its absolute quality or price level.

The model with one random coefficient, so called the vertical model, represents a market where consumers agree on product quality but they differ in their willingness to pay for quality improvement. Sources of difference are mainly differences in income and/or tastes on product characteristics. This model is fit to describe the market where products consist of characteristics which all consumers prefer more of. In this sense the CPU is a good example. All consumers prefer higher performance chips to lower ones, but they have different valuations on the performance. However, when the model is extended to include another random coefficient, the consensus on the product ranking does not hold any more.

Price elasticity is defined as

$$\frac{\partial s_j}{\partial p_j}\frac{p_j}{s_j} = -\frac{p_j}{s_j}\left(f\left(\frac{\delta_j - \delta_{j-1}}{p_j - p_{j-1}}|\boldsymbol{\theta}\right)\frac{\delta_j - \delta_{j-1}}{(p_j - p_{j-1})^2} + f\left(\frac{\delta_{j+1} - \delta_j}{p_{j+1} - p_j}|\boldsymbol{\theta}\right)\frac{\delta_{j+1} - \delta_j}{(p_{j+1} - p_j)^2}\right), \tag{8a}$$

$$\frac{\partial s_j}{\partial p_{j-1}}\frac{p_{j-1}}{s_j} = \frac{p_{j-1}}{s_j}\left(f\left(\frac{\delta_j - \delta_{j-1}}{p_j - p_{j-1}}|\boldsymbol{\theta}\right)\frac{\delta_j - \delta_{j-1}}{(p_j - p_{j-1})^2}\right), \tag{8b}$$

$$\frac{\partial s_j}{\partial p_{j+1}}\frac{p_{j+1}}{s_j} = \frac{p_{j+1}}{s_j}\left(f\left(\frac{\delta_{j+1} - \delta_j}{p_{j+1} - p_j}|\boldsymbol{\theta}\right)\frac{\delta_{j+1} - \delta_j}{(p_{j+1} - p_j)^2}\right), \tag{8c}$$

$$\frac{\partial s_j}{\partial p_{j+r}}\frac{p_{j+r}}{s_j} = 0, \quad for \;\; r = \pm 2, \pm 3, ... \tag{8d}$$

As equations (8a)-(8d) show, the price elasticity depends on cutoff points, the *pdf* of α at cutoff points and the price differences between two adjacent products. Moreover, the cross elasticities with respect to products not located in the adjacent neighborhood are all zero, which means that these products are not substitutes to product j.

It is worth comparing the vertical model with the model that is often used in empirical

Industrial Organization. If I add a multivariate extreme value error term that is *i.i.d.* across products and consumers, *i.e.*

$$u_{ij} = \delta_j - \alpha_i p_j + \varepsilon_{ij}, \tag{9}$$

then I have a multinomial logit model with random coefficients. The presence of the extreme value error term gives market share equations which are smooth and continuous over all parameter values, *i.e.*

$$s_j = \int \frac{\exp\left(\delta_j - \alpha_i p_j\right)}{1 + \sum_{m=1}^{J} \exp\left(\delta_m - \alpha_i p_m\right)} dF\left(\alpha_i|\boldsymbol{\theta}\right) \tag{10}$$

Since the market share of product j is a function of all other products, it imposes a substitution pattern that all products in the market should be substitutes to one another.

The vertical model and the logit family model respectively represent two extreme cases. In the random coefficient logit model, the price elasticity is defined as

$$\frac{\partial s_j}{\partial p_k}\frac{p_k}{s_j} = \begin{cases} -\frac{p_j}{s_j}\int \alpha_i s_{ij}\left(1 - s_{ij}\right) dF\left(\alpha_i|\boldsymbol{\theta}\right), & \text{if } j = k; \\ \frac{p_k}{s_j}\int \alpha_i s_{ij} s_{ik} dF\left(\alpha_i|\boldsymbol{\theta}\right), & \text{otherwise} \end{cases} \tag{11}$$

where $s_{ij} = \frac{\exp(\delta_j - \alpha_i p_j)}{1+\sum_{m=1}^{J}\exp(\delta_m \beta - \alpha_i p_m)}$. Equation (11) shows that products are substitutes to all other products and the degree of substitution is determined by market shares and a price coefficient.

4 Estimation Strategy

I assume that product quality depends linearly on the observable and unobservable characteristics such that at time t

$$\delta_{jt} = \mathbf{x}_{jt}\boldsymbol{\beta} + \xi_{jt}, \tag{12}$$

where $\mathbf{x}_{jt}$ represents the observed characteristics and ξ_{jt} represents the unobserved characteristics. I use two specifications for $\mathbf{x}_{jt}$. In one specification, $\mathbf{x}_{jt}$ includes the constant term, the processor speed (divided by 100), the processor speed squared and a dummy variable for processors without L2 cache (No_Cache). In another specification, $\mathbf{x}_{jt}$ includes the constant term, the processor speed, dummy variables for the lithography technology ($Dtech$) and a dummy variable for processors without L-2 cache. ξ_j consists of any characteristics that the consumer observes but the econometrician does not. Stability and reputation are good examples. I use two specifications for $\mathbf{x}_{jt}$.

I also incorporate two types of time effects into consumer utility. One is an effect of yearly changes in unobservable characteristics and the other is an effect of yearly changes in the value of choosing the outside option. The first effect will be captured by dividing ξ_{jt} into ξ_t and $\triangle\xi_{jt}$ where $\triangle\xi_{jt} = \xi_{jt} - \xi_t$ and $E\left(\triangle\xi_{jt}\right) = 0$ and the second effect will be captured by allowing δ_{0t} to vary year by year. Now the consumer utility becomes

$$\begin{aligned} u_{ijt} &= \delta_{jt} - \alpha_i p_{jt} = \mathbf{x}_{jt}\boldsymbol{\beta} - \alpha_i p_{jt} + \xi_t + \triangle\xi_{jt}, \\ u_{i0t} &= \delta_{0t} \end{aligned} \tag{13}$$

for $t = 1, 2, ..., T$. However, I am not able to identify both effects separately, but only the sum of these two effects. I can also include ξ_j to test if $\triangle\xi_{jt}$ contains a product specific omitted variable; in other words, having ξ_j will test if $E\left(\triangle\xi_{jt}\right) = 0$ with respect to j.

With the time effect the market share of the outside option for year t becomes[15]

$$s_{0t} = 1 - F\left(\frac{\delta_{1t} - \delta_{0t}}{p_{1t}}|\boldsymbol{\theta}\right). \tag{14}$$

With data on prices and market shares and the parametric assumption on the distribution, I calculate the product quality for each product in the following way. For given $\boldsymbol{\theta} = \boldsymbol{\theta}^1$, I obtain the product quality for the lowest quality product by inverting the market share equation of the outside option. So from equation (14)

$$\delta_{1t} - \delta_{0t} = p_{1t}F^{-1}\left(1 - s_{0t}|\boldsymbol{\theta}^1\right). \tag{15}$$

Then from

$$s_{1t} = F\left(\frac{\delta_{1t} - \delta_{0t}}{p_{1t}}|\boldsymbol{\theta}^1\right) - F\left(\frac{\delta_{2t} - \delta_{1t}}{p_{2t} - p_{1t}}|\boldsymbol{\theta}^1\right), \tag{16}$$

I obtain

$$\delta_{2t} - \delta_{0t} = (\delta_{1t} - \delta_{0t}) + (p_{2t} - p_{1t})\, F^{-1}\left(1 - s_{0t} - s_{1t}|\boldsymbol{\theta}^1\right). \tag{17}$$

[15] If both δ_0 and p_0 are assumed to be zeros, $s_0 = F\left(\frac{p_1}{\delta_1}|\theta\right)$.

More generally,

$$\left(\delta_{jt}-\delta_{0t}\right)=\left(\delta_{j-1,t}-\delta_{0t}\right)+\left(p_{jt}-p_{j-1,t}\right)F^{-1}\left(1-s_{0t}-s_{1t}-...-s_{j-1,t}|\boldsymbol{\theta}^{1}\right) \tag{18}$$

for $j = 2, ..., J$.

With $\widetilde{\delta}_{jt} = (\delta_{jt} - \delta_{0t})$ calculated recursively as above, I estimate $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ from

$$\widetilde{\boldsymbol{\delta}} = \boldsymbol{\delta} - \boldsymbol{\delta}_0 = X\boldsymbol{\beta} + D\boldsymbol{\gamma} + \triangle\boldsymbol{\xi} \tag{19}$$

where $X = \left[\mathbf{1}\ \ Speed\ \ (Speed)^2\ \ No\_Cache\right]$ or $X = [\mathbf{1}\ \ Speed\ \ Dtech\ \ No\_Cache]$ and $D = [d_{t1}\ d_{t2}...d_{t7}]$, $d_{tk} = 1$ if $t = k$ and 0 otherwise. It is now clear why I cannot separate the two time effects; I estimate all time effects with a single set of year dummy variables, D. If the value of the outside option is zero for all years, $\boldsymbol{\gamma}$ captures yearly changes in unobservable characteristics. On the other hand, if $\xi_t = 0$ for all years, in other words the mean value of unobservable characteristics is zero for all years, $\boldsymbol{\gamma}$ captures yearly changes in the value of the outside option.

However, Pakes, Berry, and Levinsohn (1993) suggests one method of recovering δ_{0t}, based on a reasonable assumption. The assumption is that, on average, the unobservable characteristics of continuing products do not change over time. Then, the average difference between δ_{jt} and $\delta_{j,t-1}$ of the continuing products indicates a change in the value of the outside option from $t-1$ to t. In order to apply this method to identify the value of the outside option, I also use the quarter dummy variables in estimating demand.

I use the generalized method of moments to estimate $\Omega = (\boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\theta})$ with moment conditions

$$E\left(Z'\Delta\boldsymbol{\xi}\right) = 0 \tag{20}$$

where Z includes the processor speed interacted with the year dummy variables, *i.e.* $Speed \times Dyear$, and all other variables: $Dtech$, No_Cache and $Dyear$. A reason that I create $Speed \times Dyear$ variables is that I need more moment conditions than the number of coefficients on X and D in order to identify parameters of the distribution ($\boldsymbol{\theta}$) along with the coefficients on X and D.[16] The processor speed interacted with the year dummies provides us with a good proxy for the cost of making processors for each year and it is reasonable to assume that this is orthogonal to the unobserved characteristics, $\Delta\boldsymbol{\xi}$.[17]

Therefore, given $\boldsymbol{\theta} = \boldsymbol{\theta}^1$, I search for $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ that minimizes

$$q\left(\Omega_1\right) = \Delta\boldsymbol{\xi}\left(\Omega_1\right)' ZWZ'\Delta\boldsymbol{\xi}\left(\Omega_1\right) \tag{21}$$

where $W = (Z'Z)^{-1}$ and $\Delta\boldsymbol{\xi}\left(\Omega_1\right) = \widetilde{\delta}\left(\boldsymbol{\theta}^1\right) - X\boldsymbol{\beta} - D\boldsymbol{\gamma}$.

After estimating $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ given $\boldsymbol{\theta} = \boldsymbol{\theta}^1$, I set $\boldsymbol{\theta}$ at another value, say $\boldsymbol{\theta}^2$, and calculate $\widetilde{\boldsymbol{\delta}}$ recursively by inverting the market share equations. Then I obtain $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ that minimizes

$$q\left(\Omega_2\right) = \Delta\boldsymbol{\xi}\left(\Omega_2\right)' ZWZ'\Delta\boldsymbol{\xi}\left(\Omega_2\right). \tag{22}$$

[16] An alternative estimator is the maximum likelihood estimator. Assuming the distribution of δ conditional on observed characterisitics is i.i.d. normal, we search for θ that maximizes the log likelihood function.

[17] We don't have the price endogeneity problem that the logit family model has, because the product quality doesn't depend on price in this model.

We repeat this procedure for all possible values of $\boldsymbol{\theta}$ and choose $\widehat{\boldsymbol{\theta}}$ such that[18]

$$\widehat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} q\left(\Omega\right) \tag{23}$$

and the GMM estimates for $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ are

$$\begin{pmatrix}\widehat{\boldsymbol{\beta}}_{GMM} & \widehat{\boldsymbol{\gamma}}_{GMM}\end{pmatrix}' = \arg\min_{\boldsymbol{\beta},\boldsymbol{\gamma}} q\left(\boldsymbol{\beta},\boldsymbol{\gamma},\widehat{\boldsymbol{\theta}}\right) = \arg\min_{\boldsymbol{\beta},\boldsymbol{\gamma}} \Delta\boldsymbol{\xi}\left(\boldsymbol{\beta},\boldsymbol{\gamma},\widehat{\boldsymbol{\theta}}\right)' ZWZ'\Delta\boldsymbol{\xi}\left(\boldsymbol{\beta},\boldsymbol{\gamma},\widehat{\boldsymbol{\theta}}\right). \tag{24}$$

However, the moment conditions described above do not reflect possible correlation in the demand disturbances of a given model across time. Although this plausible correlation does not affect the consistency or asymptotic normality of the estimates, it affects their variance-covariance matrix. Therefore, I treat the sum of the moment conditions of a given product over time as a single condition. While this produces the same estimates as before, it allows more correlation in the disturbances of the same model over time than in the disturbances of different models.[19]

5 Results

5.1 Estimates

For the distribution of α I have chosen the log normal distribution with the variance parameter set at 1 such that $\log\left(\alpha\right) \sim N\left(\theta_1, 1\right)$, and the gamma distribution with the shape parameter set at 1; *i.e.*, the exponential distribution.

[18] A practical way of doing this is to set a grid for θ and try every value in the grid one by one.
[19] For more details, see Berry, Levinsohn, and Pakes (1995).

Table 2 shows estimation results on $\Omega = (\boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\theta})$. The first two columns are the log normal distribution case and the last two columns are the exponential distribution case. Since the model is based on the ordinal utility function, I normalize the constant term at -6. Both coefficients and standard errors change in proportion to changes in the constant term, but the price elasticity and consumer welfare are not affected by which level the constant term is fixed at.[20]

The estimates of the product characteristics show that product quality is a concave function of the processor speed. The coefficients on the technology dummy variables suggest that an increase of the processor speed in the late 1990s is not as much appreciated as before. Caution should be exercised, however, when interpreting the estimates of the technology dummy variables. The processor speed is determined by the technology used. So we should look at both the speed coefficient and the technology coefficients to relate product characteristics to product quality. For example, until 1998 Intel manufactured processors with 0.35 micron photolithography, and the maximum processor speed was 300 Mhz. In the second quarter of 1998 Intel began to adopt 0.25 micron technology, and the processor speed went up to 400 Mhz. The quality difference between 300 Mhz and 400 Mhz processors produced in 1998 is $\triangle\delta = \widehat{\beta}_{Speed} \times (4-3) + \left(\widehat{\beta}_{Dtech4} - \widehat{\beta}_{Dtech3}\right)$. $\triangle\delta$ is 1.45 for the log normal distribution and 1.51 for the exponential distribution.

As mentioned earlier, the coefficients on year dummies capture a mixture of yearly changes in unobservable characteristics and yearly changes in the value of the outside option. If I assume that the value of the outside option is zero for all years, the coefficients on year dummies tell us that the mean utility from unobservable characteristics went down since 1997. Or if I assume that

[20] For example, if the constant term is fixed at -12, all coefficients and standard errors are doubled but price elasticity and consumer welfare are not changed.

the mean value of unobservable characteristics is zero for all years, the year dummy coefficients tell us that the value of not buying Intel and AMD products went up since 1997.[21]

However, as explained in the previous section, I separate the value of the outside option from the unobservable characteristics, using the continuing products. For this purpose, I include the quarter dummy variables instead of the year dummy variables in the explanatory variables. The estimates of the product characteristics hardly change. For example, for the first specification of the log normal distribution case, I have 1.74 (0.30) for the parameter of the distribution, 2.40 (0.71) for the processor speed, -0.14 (0.04) for the processor speed squared, and -0.72 (0.23) for the No_Cache variable, with standard errors reported in parentheses.

Figure 4 illustrates the time trends of the value of the outside option and the value of the unobservable characteristics. Since only $\delta_{0t} - \delta_{0,t-1}$ is identified, I assume that the value of the outside option in 1993 is zero. The figure shows that the value of the outside option increases since 1997. This is quite surprising, since the combined market share of Intel and AMD kept increasing in the late 1990s. Although Intel lost a 14% of its market share in 1998, it quickly recovered a large part of its loss by slashing prices of the Celeron CPU, and AMD was steadily taking up more market shares with the success of its K6 series in the late 1990s.

However, changes in the market share do not necessarily reflect changes in the value of the outside option. Firms can increase its market share by lowering the price. If a drastic price cut does not attract “enough" consumers from the outside, this may suggest that the value of the outside option goes up. Since 1998, Intel has aggressively set its price, especially at the low end,

[21] Coefficients on dummy variables shows that $\delta_t - \delta_{0t}$ goes down as t goes up controlling product characteristics, which means that δ_{0t} goes up as t goes up.

and it succeeded in increasing the market share. Nevertheless, the value of the outside option still increased, and this is why some consumers still choose the outside option, despite declining prices of Intel and AMD products.

The figure also shows that the value of unobservable characteristics decreases in the late 1990s. It was quite stable until the end of 1997, and it starts declining with more frequent introductions of new products. This suggests that Intel and AMD have not improved other characteristics, although they succeeded in increasing the processing speed. One important unobservable characteristic is power consumption. As the speed goes up, the amount of electricity that processors consume increases considerably. As a result, the processor tends to heat up easily, and becomes unstable if it is not effectively cooled down. The power consumption issue and the associated instability have become the main concerns of the industry.

Since the two distributions do not produce significantly different estimates, I will focus on the log normal distribution case from now on.

5.2 Price Trends and Elasticity

The demand model used in the previous sections has market shares determined by the area each product occupies under the distribution of the random coefficient. The boundary points of each interval are quality difference divided by price difference between two adjacent products. Therefore, although firms keep introducing new products with more advanced technology, and their performance exceeds that of existing products, the product location of the highest performance product is always the left end of the distribution, and consumers who put the highest value on product quality buy this product. The market share of this best product is determined by how much better it is relative to the second best product in the market, and by how much expensive it is. Once a product is introduced in the market, its product location moves along the distribution of the random coefficient as higher quality products keep entering the market, and its price follows the same path as the new product in the previous period followed.

In order to examine how the price elasticity changes as products change their locations in the distribution, I calculate the elasticity for each product based on the estimation results. The price elasticity shows us how sensitive consumers in different sections of the distribution are to price changes, and it enables us to infer how markup changes during the product lifespan.[22] The microprocessor industry is well known for a high sunk cost for plants and equipment. So in order to recover the sunk cost firms should set a high markup at some point during the short product lifespan, which is six to eight quarters on average.

In Table 3, I report the price elasticities and semi-elasticities of six products for five consecutive quarters. Although all six products were introduced at different points of time, they share common trends of price and (semi) elasticity: prices rapidly decline and (semi) elasticities go up as prices decline. For example, the Pentium III of 400 Mhz speed entered the market in the second quarter of 1998. For five quarters while the product was in the market, the price dropped from \$773 to \$200. On the other hand, the elasticity went up from around -6 to -34.8. That means at the time of the introduction, a 1% change in price induced a 6% change in market share, and just before the product exited the market, a 1% change in price induced a 34.8% change in market share. In terms of semi-elasticity, it means that if the price goes down by \$10, the market share

[22]However, I report only own price elasticity. In order to obtain cross price elasticity and markups, I need more detailed data on products by AMD.

goes up by 8% (from 0.0228 to 0.0246) in the first quarter of introduction, but it goes up by 174% (from 0.078 to 0.2137) just before it exits the market.

Figure 5 depicts price and elasticity of 500Mhz Pentium III processor and Figure 6 compares price and semi-elasticity of three processors that entered the market at different points of time. We observe that the trends of both price and elasticity are very similar. The resemblance of the trend is not confined to these three products. Although there are some differences, most of products in the data set follow very similar trend.

The pattern of elasticity implies that consumers who buy new products are relatively less sensitive to price changes than those who buy existing products. This also implies that the firm is able to set a high markup in the early period of the product life. This is consistent with what industry experts say.[23] As soon as a production line reaches a mature stage which takes six months or so, the marginal cost of production does not vary much for the rest of the product life. Therefore, a firm that introduces a new product first reaps high variable profit by setting a high price in the early period of the product life. This explains a firm's incentive to occupy the high end of the market.

The pattern of elasticity also shows changes in the degree of competition that products go through during their product life. While Intel products dominate at the high end, products are more closely located at the low end, since AMD products compete with Intel products there. Indeed, the elasticities indicate that some products face almost perfect competition before they exit the market.[24]

[23] Gwennap and Krewell (2000)

[24] When firms make processors from a single wafter, they do not have perfect control on the processor speed of products they produce. This sometimes causes variation in speed among products from the same wafer, and as a

6 Consumer Welfare

Since the utility of consumer i who buys product j at period t is defined as

$$u_{ijt} = \delta_{jt} - \alpha_i p_{jt}, \tag{25}$$

I need to divide u_{ijt} by α_i in order to measure consumer welfare in monetary units. Therefore, consumer welfare at period t is

$$\begin{aligned} CW_t &= \sum_{j=1}^{J} \sum_{i \in j} \frac{1}{\alpha_i} \left(u_{ijt} - u_{0t} \right) \\ &= \sum_{j=1}^{J} \sum_{i \in j} \frac{1}{\alpha_i} \left(\delta_{jt} - \delta_{0t} \right) - \sum_{j=1}^{J} \sum_{i \in j} p_{jt} \\ &\approx \sum_{j=1}^{J} E\left(\frac{1}{\alpha_i} | i \in j \right) q_{jt} \left(\delta_{jt} - \delta_{0t} \right) - \sum_{j=1}^{J} p_{jt} q_{jt} \end{aligned} \tag{26}$$

where $i \in j$ indicates a group of consumers who buy product j at time t and q_{jt} is the quantity of product j sold at time t.

It is important to note that the welfare calculation is free from the extreme value error term or tastes for products that typical discrete choice empirical models have. A problem with the model with tastes for products becomes severe when it comes to measuring benefits from introducing new products, because the model assumes that there are consumers who prefer new products regardless of their characteristics. Petrin (2002) shows that in demand models with the idiosyncratic error term, a large part of welfare changes comes from the error term. Until he interacts the idiosyncratic

result some products of the same firm are too closely located.

error with consumer demographic data, the model misleadingly implies that consumers strongly dislike the observed characteristics relative to their alternative choice. However, consumer welfare, calculated here, directly reflects consumers' valuation of product characteristics.

I use two ways of dealing with δ_{0t}. One way is to assume that the utility from the outside option is zero for all periods; *i.e.*, $u_{0t} = 0$ for all t, so that δ_{0t} disappears from equation (26). Another way is to separate δ_{jt} from $\delta_{jt} - \delta_{0t}$ by adding δ_{0t} obtained in the previous section. In both cases, consumer welfare represents the total benefits consumers in the world CPU market gain from buying Intel and AMD CPUs. Alternatively, consumer welfare, calculated by the first way, can be interpreted as the consumers' relative gains of buying Intel and AMD products, compared with buying other products.

The first two columns in Table 4 report consumer welfare, calculated by these two ways, for the log normal distribution of α, from 1996 to 2000, and Figure 7 illustrates the time trends.[25] Although the overall trend is similar, a huge difference occurs in 1999 and 2000. When I account for changes in the value of the outside option, the welfare calculation produces lower consumer welfare for periods before 1998, and higher consumer welfare for 1999 and 2000.

The increase of welfare in the late 1990s coincides with a higher rate of innovation in the semiconductor industry. In 1998 the semiconductor industry led by SEMATECH, a joint research consortium formed by semiconductor manufacturers, switched to a 2 year product cycle from a 3 year product cycle. This means that SEMATECH started introducing a new lithography technology every two years instead of every three years. This shortened the interval between new products

[25] One should note that the data set doesn't include 386 and 486 processors which were produced until 1995. So welfare and variable profit only reflect benefits from Pentium and better processors, and this is why I do not include consumer welfare before 1996.

entering the market, and the welfare trend reflects consumer benefits from this more frequent entry of new products.

The increase in welfare in this period also coincides with the success of Celeron CPUs. Since Celeron class processors do not have an external cache, firms were able to lower the production cost as well as prices.[26] For example, in the first quarter of 1999 the Pentium II 400 Mhz processor was sold at $353 while the same speed Celeron processor was sold at $158. However, for simple tasks like using the internet and word processing, they provide only slightly less performance than equivalent Pentium processors, although they are much inferior for computational tasks.

Before the introduction of Celeron products, firms targeted consumers at the low end of the market with the previous generation products. Now firms have shortened product lifespans, and introduce new products at the low end of the market. Consequently, consumers at the low end of the market enjoy better performance products than before, and this is reflected in consumer welfare as gains.

I decompose consumer welfare by consumer groups, in order to examine how much of consumer welfare is generated in different parts of the market. Figure 8 shows the average welfare gains of each group of consumers in the first quarter of 2000. Consumers on the left end are those who bought a just released Pentium III 1 Ghz CPU and they gain $6,700 on average. Consumers in the second group, *i.e.* those who bought a few month old Pentium III 800 Mhz processor, gain $2,700 on average. From the sixth group on, the gain falls below $1,000, and the groups in the far low end gain less than $100. The graph does not change much across time in the sense that the

[26] The unit cost of production for Celeron processors is around $50, while the production cost of Pentium II processors is about $150.

first group gains \$5,000 to \$7,000 on average, and the average gain drops to \$1,000 at the third or fourth group.[27]

It is also worth decomposing consumer welfare by products for the following reason. Due to product obsolescence, a welfare implication for consumers at the low end of the market is ambiguous. Consumers at the low end may be forced to buy better performance CPUs, because products they really want to buy are not available in the market. However, consumers at the high end clearly benefit from new products. They can buy the same quality products they bought in the last period at much lower prices. Therefore, it is important to show how much welfare products at the high end generates, in order to evaluate an implication of welfare increases.

Figure 9 illustrates the fractions of consumer welfare generated by the highest quality product and the three highest quality products. Although the fractions fluctuate over time, the figure shows that a huge part of consumer welfare comes from products at the high end, often new products. One should note that exceptionally high ratios in 1998 are due to the relatively small number of products in the market in that year. The figure also shows that the fractions are higher on average in later years of the sample period.

The third and fourth columns of Table 4 and Figure 10 show firms' variable profit, which is defined as $\pi_t = \sum_{j=1}^{J} (p_{jt} - mc_{jt}) \, q_{jt}$, and R&D expenditures. The marginal cost is the average manufacturing cost of CPUs at maturity, and it is estimated by MicroDesign Resources. However, the cost data are not product-specific, but the average cost of each generation. The profit trend is very cyclical, with peaks in the fourth quarter of 1995, the second quarter of 1997, the third

[27] One caveat is that consumers include business firms as well as households. Therefore, consumer welfare calculated here may capture benefits accrued to firms who use computers.

quarter of 1998, and a huge one in the first quarter of 2000, and with troughs in the second quarter of 1996, the fourth quarter of 1997 and the second quarter of 1999. The R&D expenditures steadily increase, and they exceed a billion dollars in 1999.

Figure 11 compares consumer welfare with the variable profit, and the last two columns of Table 4 report a ratio of consumer welfare to social surplus. Although the variable profit fluctuates over time, it looks quite stable when it is put together with consumer welfare. The table shows that consumer welfare consists of about 90% of total social surplus in the late 1990's, which suggests that consumers gain much more than firms from more frequent innovation. If I use the R&D expenditures as a proxy for the cost of innovation, these results also show that the social return on firms' research investment is much higher than the return to firms. This is because consumers continue to enjoy more benefits from frequent introduction of new products and declining price, while firms earn limited profits due to competition and carnibalization of existing products by new products.

Competition is a very important factor that explains the huge discrepancy between consumer welfare and firms' profits. There are consumers who are willing to pay a much higher price for new generations of processors, but firms do not fully extract reservation values. In Section 8 I simulate a multiproduct duopoly market based on the demand model and estimates, in order to examine how competition drives down prices at the high end of the market.

7 Model Extension

As explained above, Intel and AMD produce two classes of processors. The only difference between these two classes is that Celeron and Duron do not have the level-2 cache. With the extra cache that stores certain data during computation, the processor does not have to communicate with the memory chip every time it uses data, and it speeds up computational operations. Therefore, I can think of a model in which people evaluate product quality in two aspects. One aspect is whether a processor has the level-2 cache or not, and the other aspect is how good a processor is in terms of all other characteristics.

Under this assumption the utility function becomes

$$\begin{aligned} u_{ijt} &= \mathbf{x}_{jt}^{-s}\boldsymbol{\beta}^{-s} + x_{sjt}\beta_{is} - \alpha_i p_{jt} + \xi_t + \triangle\xi_{jt}, \\ u_{i0t} &= \delta_{0t} \end{aligned} \tag{27}$$

where $\mathbf{x}_j^{-s}$ includes all the observable characteristics except for $x_{sjt} = No\_Cache$ and $\beta_{is} \sim_{i.i.d.} G(.)$. Assuming that $\beta_{is} \sim N\left(\beta_s, \sigma^2\right)$,

$$\begin{aligned} u_{ijt} &= \mathbf{x}_{jt}\boldsymbol{\beta} + x_{sjt}\sigma\upsilon_i - \alpha_i p_{jt} + \xi_t + \triangle\xi_{jt} \\ &= \delta_{jt} + x_{sjt}\sigma\upsilon_i - \alpha_i p_{jt} \\ u_{i0t} &= \delta_{0t} \end{aligned} \tag{28}$$

where $\delta_{jt} = \mathbf{x}_{jt}\boldsymbol{\beta}+\xi_t + \triangle\xi_{jt}$ with $\mathbf{x}_{jt}$ including all the observable characteristics and $\upsilon_i \sim N(0,1)$. Now the product ordering on the single dimension does not hold any more. Instead, each consumer evaluates product quality as $\delta_{ijt} = \delta_{jt} + \sigma \upsilon_i x_{sjt}$. However, if σ is zero, this model returns to the vertical model.

Following Berry and Pakes (2002) I can obtain market shares conditional on β_{si} and then integrate over the β_{si} distribution; *i.e.*,

$$s_j(\boldsymbol{\delta}, \mathbf{p}; \Omega, F, G) = \int \left(F\left(\overline{\triangle}_{ij}(\delta, p, \beta_{si}) | \boldsymbol{\theta}, \beta_{si}\right) - F\left(\underline{\triangle}_{ij}(\delta, p, \beta_{si}) | \boldsymbol{\theta}, \beta_{si}\right)\right) 1\left\{\overline{\triangle}_{ij} > \underline{\triangle}_{ij}\right\} dG(\beta_{si}), \tag{29}$$

for $j = 0, ..., J$. Now the cutoff points for consumer i who is endowed with α_i and β_{si} are

$$\overline{\triangle}_{ij} = \min_{k<j} \frac{(\delta_j - \delta_k) + \sigma \upsilon_i (x_{sj} - x_{sk})}{p_j - p_k} \text{ and} \tag{30a}$$

$$\underline{\triangle}_{ij} = \max_{k>j} \frac{(\delta_k - \delta_j) + \sigma \upsilon_i (x_{sk} - x_{sj})}{p_k - p_j}. \tag{30b}$$

Since equation (29) is usually not analytic, I use a simulation estimator which is an unbiased estimator of the integral. Now the market share is approximated by

$$s_j(\boldsymbol{\delta}, \mathbf{p}; \Omega, F, G_{ns}) = \frac{1}{ns} \sum_{i=1}^{ns} \left(F\left(\overline{\triangle}_{ij}(\delta, p, \beta_{si}) | \boldsymbol{\theta}, \beta_{si}\right) - F\left(\underline{\triangle}_{ij}(\delta, p, \beta_i) | \boldsymbol{\theta}, \beta_{si}\right)\right) 1\left\{\overline{\triangle}_{ij} > \underline{\triangle}_{ij}\right\} \tag{31}$$

where G_{ns} denotes the empirical distribution of the simulated β_{si}.

In this model, recovering $\boldsymbol{\delta}$ from the share equation is not as straightforward as the vertical model. Instead of relying on analytic solutions, I search for the $\boldsymbol{\delta}$ that equates market shares predicted by the model to real market shares from data.[28] Once I obtain $\boldsymbol{\delta}$, I use the method of

[28] For details of the search algorithm, see Berry and Pakes (2002).

moments to estimate $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ in exactly the same way as I did with the vertical model.

In Table 5, I compare estimation results for the pure characteristics model with the vertical model for $\alpha \sim LN(\theta, 1)$ and $\beta_{si} \sim N(\beta_s, \sigma^2)$. The table shows that $\beta_{si} \sim N\left(-2.93, (2.46)^2\right)$, and that they are statistically significant. All estimates on product characteristics are now higher (except for the dummy variable for the second generation technology, $Dtech2$).

Figure 12 shows consumer welfare in the pure characteristics model, and Figure 13 adds consumer welfare in the vertical model to Figure 12 for comparison.[29] Figure 13 shows that consumer welfare is higher in the pure characteristics model. This suggests that there are consumers who less care about performance differences caused by the absence of the level-2 cache than others, or that there are also consumers who value CPUs with the level-2 cache more than others. By having another random variable, the model becomes more flexible in reflecting consumers' preference, which results in higher consumer welfare.

8 Effect of Quality Competition on Price

AMD as a main rival of Intel has kept introducing new products following Intel. Usually Intel comes up with new generations first and then AMD follows with some time lag. In other words, AMD

[29] The consumer welfare for the pure characterisitic model is calculated as

$$\begin{aligned} CW_t &= \sum_{j=1}^{J} \sum_{i \in j} \frac{1}{\alpha_i} (u_{ijt} - u_{0t}) \\ &= \sum_{j=1}^{J} \sum_{i \in j} \frac{1}{\alpha_i} (\delta_{jt} - \delta_{0t}) + \sum_{j=1}^{J} \sum_{i \in j} \frac{1}{\alpha_i} \upsilon_i x_{sjt} \widehat{\sigma} - \sum_{j=1}^{J} \sum_{i \in j} p_{jt}. \\ &\approx \sum_{j=1}^{J} q_{jt} \left(E\left(\frac{1}{\alpha_i} | i \in j \right) (\delta_{jt} - \delta_{0t}) + E\left(\frac{1}{\alpha_i} | \upsilon_i, i \in j \right) E(\upsilon_i | i \in j) x_{sjt} \widehat{\sigma} - p_{jt} \right). \end{aligned}$$

has introduced new products just below Intel's new processors in the distribution. This quality competition between these two firms is likely to keep price at the high end of the market from rising despite quality improvements.

Figure 2 shows the time paths of four different processors introduced at different points of time. They not only follow a similar price path but the price range is also similar. For example, Pentium II 333 Mhz processor was introduced at $738 in the fourth quarter of 1997 and its price dropped to $275 in one year. Two years later Pentium III 600 Mhz was introduced at $745 and its price dropped to $183 in one and a half years.

8.1 Setup

In the market there are two firms that each produce two types of products: a high quality product and a low quality product. Given two products of a firm at a certain period, I call a product whose quality is higher the "frontier" product and the lower quality product the "non-frontier" product. For example, in 1997 the frontier product of Intel was a Pentium II chip, while the non-frontier product was a Pentium MMX chip. In 2000 Intel produced Pentium III chips as the frontier products and Celeron chips as the non-frontier products.

For computational simplicity I assume that the consumers' valuation on product quality has the exponential distribution. Therefore, the model is

$$
\begin{aligned}
u_{ijt} &= v_i \delta_{jt} - p_{jt}, \\
u_{i0t} &= \delta_{0t} \qquad (32)
\end{aligned}
$$

where v ~exponential(λ) . Under this model the estimate of λ is 0.53 with a standard error of 0.26.

The firm is identified by the pair of qualities for products that it produces. And since this is a duopoly market, two pairs of product qualities determine the market structure. For example, $\{(4,1),(3,2)\}$ means that firm 1 produces a frontier product of quality 4 and a non-frontier product of quality 1, while firm 2 produces a frontier product of quality 3 and a non-frontier product of quality 2. More generally, I denote the market structure as $\{(\omega_{1f},\omega_{1n}),(\omega_{2f},\omega_{2n})\}$ where the first subscript identifies firms and the second subscript indicates whether a product is a frontier or a non-frontier one.

I set a grid for ω from 0.5 to 3.5 with a 0.5 interval. According to the estimation results, the product quality ranges from 0.1 to 3.6 under the exponential distribution with $\lambda = 0.53$. The estimates on coefficients of product characteristic variables provide us with ways to interpret a 0.5 quality difference. For two processors produced with the same lithography technology a 0.5 quality difference means that one processor does not have the level-2 cache and the speed is 110 Mhz lower than the other processor. If both of the two products produced with the same lithography technology have the level-2 cache, a 0.5 difference means that the processor speed of one processor is 300 Mhz lower than the other processor. If one processor is produced with 0.35 $m\mu$ technology and the other is produced with 0.25 $m\mu$ technology, a 0.5 difference means one processor is 425 Mhz slower than the other processor.

8.2 Algorithm

Given products on the quality line, firms set prices to maximize profits, which results in a Bertrand Nash equilibrium. The profit equation of a firm is

$$\pi = (p_f - mc_f)\, s_f M + (p_{nf} - mc_{nf})\, s_{nf} M \tag{33}$$

where p is price, mc is the marginal cost, s is market share and M is the market size. The subscript f stands for the frontier product and nf stands for the non-frontier product.

The first order condition of profit maximization differs depending on the location of products on the quality line. If two products are located next to each other, the first order conditions are

$$\frac{\partial \pi}{\partial p_f} = s_f + \frac{\partial s_f}{\partial p_f}(p_f - mc_f) + \frac{\partial s_{nf}}{\partial p_f}(p_{nf} - mc_{nf}) = 0 \tag{34a}$$

$$\frac{\partial \pi}{\partial p_{nf}} = s_{nf} + \frac{\partial s_{nf}}{\partial p_{nf}}(p_{nf} - mc_{nf}) + \frac{\partial s_f}{\partial p_{nf}}(p_f - mc_f) = 0 \tag{34b}$$

However, if two products are not located next to each other, in other words if a product of a rival firm is located between two products of a firm, the first order conditions become

$$\frac{\partial \pi}{\partial p_f} = s_f + \frac{\partial s_f}{\partial p_f}(p_f - mc_f) = 0 \tag{35a}$$

$$\frac{\partial \pi}{\partial p_{nf}} = s_{nf} + \frac{\partial s_{nf}}{\partial p_{nf}}(p_{nf} - mc_{nf}) = 0 \tag{35b}$$

This difference comes from the substitution pattern of the vertical demand model. As shown in equations ($8a$) to ($8d$) , only adjacent products are substitutes for one another. Therefore, if a firm produces two products that are separated on the quality line by a rival firm's product, it sets prices as if it sells two products in two separate markets.

Given all possible combinations of product qualities, I search for prices that simultaneously satisfy the profit maximizing conditions of the two firms. I use a globally convergent Newton's method for nonlinear systems of equations.[30] This algorithm combines the rapid local convergence of Newton's method with a globally convergent strategy in order to make solutions robust to starting points.

8.3 Simulation Results

The simulation shows that for two frontier products produced by different firms, the price (of a higher quality product) is more sensitive to the quality difference with the other frontier product than to its own quality level. Comparing cases 1 and 2 with cases 3 and 4 in Table 6 shows that an increase in ω_{1f} with $\triangle\omega_f = \omega_{1f} - \omega_{2f}$ unchanged does not raise p_{1f} as much as an increase in $\triangle\omega_f$ does. We also see that with ω_{1f} fixed, p_{1f} declines drastically as ω_{2f} goes up. In Figure 14, I plot the price of firm 1's frontier product on $\triangle\omega_f = \omega_{1f} - \omega_{2f}$ with ω_{1n} and ω_{2n} fixed at 1.5 and 0.5. The graph shows that a quality increase from 3.0 to 3.5 with $\triangle\omega_f$ unchanged raises price only a little bit while a change in $\triangle\omega_f$ has a large impact on p_{1f}.

The effect of the quality difference on price manifests a role of quality competition on the price decline in the CPU market. Quality improvement of AMD's products in the lower part of the distribution drives down the price of Intel products at the high end. The magnitude of this

[30] I used computer codes in *Numerical Recipes in C* by William Press et. al (1992).

competition effect is large compared with the effect of Intel's own quality improvement.

It is worth pointing out that the model does not consider technology advances. While conventional explanations of the price decline rely on technological advances, this simulation explains price declines only with competition in the market. However, I expect that a technology factor would enhance the price decline, since new technologies decrease the unit cost of production.

9 Conclusions and Extensions

This paper estimates CPU demand using product level data, and measures consumer benefits of frequent innovation, based on the estimates and the demand model. The paper finds huge increases in consumer welfare, when the industry speeds up its innovation pace. The price declines also enhances welfare gains, and the paper shows how "quality competition" can prevent prices from arising, even when product quality keeps improving.

The welfare calculation supports the industry-wide efforts on developing new technologies. SEMATECH (The SEmiconductor MAnufacturing TECHnology), a research joint venture formed by the government in 1987 and now privately run by semiconductor manufacturers, has devoted itself to bringing new photolithography technologies into the industry. This paper provides evidence that consumers have not only gained considerable benefits from new technologies but consumers' benefits also exceed firms' profits.

However, there still remain some important questions unanswered. First, what is the socially optimal rate of innovation in this industry? Second, how do different market structures affect the rate of innovation? Third, what is the effects of having SEMATECH?

In order to explore these issues, I have constructed a dynamic model which not only includes the R&D stage, but also endogenizes product entries and exits in the product market. In another paper (Song, 2002), I use this model to examine the effects of SEMATECH. The paper compares the cooperative research regime, where firms make cooperative research investment to develop new lithography technology, with the competitive research regime. The model separates a research stage from a production stage such that firms always compete in the production stage no matter whether they compete or cooperate in the research stage. Product quality is endogenously determined by firms that maximize the expected discounted value of future net cash flow. The paper finds that the level of investment in the cooperative research regime is lower than in the competitive regime, but the probability of successful research becomes higher under cooperation. It also shows how the firms' states determine whether they cooperate or not.

This model can be extended to explore the effects of different market structures on the rate of innovation, as well as firm behavior and the evolution of market structure associated with technological advances.

Another interesting issue concerning this market is how consumer expectations affect the price trend. In a market where price is certain to fall, consumers have the option value of waiting, and the point at which a consumer buys a product is where the marginal benefit of waiting is equal to the marginal cost of waiting. A dynamic model that takes the consumers' option value into account will enable us to approach this issue.

Appendix I: Consumer Utility Maximization

Consider a rational consumer in the CPU market who maximizes her utility subject to the budget constraint.[31] I assume that consumer utility is quasilinear so that the marginal rate of substitution between the CPU and all other goods is constant for every consumer. This assumption is quite strong since consumers usually take other components like memory and storage devices into account when they buy computers. Therefore, the utility of having a certain CPU is affected by what other components consumers buy together. For example, a consumer who prefers a CPU with high clock speed is also likely to prefer large memory capacity so that the marginal utility of having a high performance CPU depends on having a large memory chip. Although the quasilinear utility function does not reflect this, the demand estimation becomes far too complicated, if indeed possible, with more general functional forms.

Another point to note is that consumers of CPUs are mainly computer manufacturers who not only buy all kinds of CPUs but also in large quantities. Therefore, a demand model in which an individual consumer decides which product to buy may not describe the data. However, I assume that purchasing decisions of computer manufacturers closely reflect those of individual consumers and that the CPU is the most important characteristic that determines the quality of computers. If a consumer's choice of which computer to buy is more affected by other characteristics like brand, this assumption would be problematic. In other words, this assumption excludes all cases where a consumer who prefers Pentium III to Pentium II nevertheless prefers a Pentium II processor computer because of other factors like brand or color.

In the CPU market with J products a consumer with the following utility function makes a purchase decision:

$$u_i\left(j,x\right) = v_i\delta_j + x$$

where δ_j is the quality of product j, v_i is the consumer's valuation of the quality and x is a numeraire commodity. So $v_i\delta_j$ is the utility that consumer i obtains from having product j. By having a random coefficient v_i on the product quality variable δ_j, consumers' different valuation on product quality is incorporated in the utility function.

Letting $\alpha_i = \frac{1}{v_i}$ and multiplying $u_i\left(j,x\right)$ by α_i,

$$u_i\left(j,x\right) = \delta_j + \alpha_i x.$$

It does not really matter where I put a random variable. If α_i is assumed to have the gamma distribution, I will obtain exactly the same estimation results with v_i on δ_j if v_i has the inverted gamma distribution. However, a reason that I put a random coefficient on x is that it facilitates comparison with the two random coefficient model in Section 7.

The consumer also faces the budget constraint. She divides her income, B, into buying product j and all other goods such that

$$\begin{aligned} x^* &= \arg\max_{x\geq 0} \delta_j + \alpha_i x \\ s.t. \quad p_j + x &\leq B. \end{aligned}$$

[31] Since a consumer is rational, her preference is complete and transitive.

This leads to $p_j + x^* = B$ and $u_i(j, x) = \delta_j + \alpha_i (B - p_j)$.

Let $j = 0$ represent the outside option and assume p_0 is zero.[32] Then the utility of the consumer in the market is

$$\begin{aligned} u_{ij} &= \delta_j - \alpha_i p_j, \quad \text{for } 1 \le j \le J \\ u_{i0} &= \delta_0 \end{aligned}$$

where income is assumed to be always higher than p_j.

Appendix II: Proof for Proposition 2

Proof. (i) Since it is trivial that $\max_{k>j} \frac{\delta_k - \delta_j}{p_k - p_j} < \min_{k<j} \frac{\delta_j - \delta_k}{p_j - p_k}$ for any j if every product has a positive market share, I only have to show $\max_{k>j} \frac{\delta_k - \delta_j}{p_k - p_j} = \frac{\delta_{j+1} - \delta_j}{p_{j+1} - p_j}$ and $\min_{k<j} \frac{\delta_j - \delta_k}{p_j - p_k} = \frac{\delta_j - \delta_{j-1}}{p_j - p_{j-1}}$ if every product has a positive market share. Suppose $\max_{k>j} \frac{\delta_k - \delta_j}{p_k - p_j} = \frac{\delta_r - \delta_j}{p_r - p_j}$ where $r > j + 1$. Consider consumers with $\alpha_i \in \left(\frac{\delta_{j+1} - \delta_j}{p_{j+1} - p_j}, \frac{\delta_r - \delta_j}{p_r - p_j} \right)$. They prefer product r to product j and prefer product j to product $j + 1$. Therefore, they must prefer product r to product $j + 1$. This implies that $\alpha_i < \frac{\delta_r - \delta_{j+1}}{p_r - p_{j+1}}$. Suppose $\frac{\delta_r - \delta_{j+1}}{p_r - p_{j+1}} < \frac{\delta_r - \delta_j}{p_r - p_j}$. Then consumers with $\alpha_i \in \left(\frac{\delta_r - \delta_{j+1}}{p_r - p_{j+1}}, \frac{\delta_r - \delta_j}{p_r - p_j} \right)$ prefer product r to product j and product $j+1$ to r. This implies that they prefer product $j+1$ to product j. However this contradicts that these consumers prefer product j to product $j + 1$. Therefore, it should be $\frac{\delta_r - \delta_{j+1}}{p_r - p_{j+1}} \ge \frac{\delta_r - \delta_j}{p_r - p_j}$ and I have $\frac{\delta_r - \delta_{j+1}}{p_r - p_{j+1}} \ge \frac{\delta_r - \delta_j}{p_r - p_j} > \frac{\delta_{j+1} - \delta_j}{p_{j+1} - p_j}$. This means that there is no consumer who buys product $j + 1$ and it contradicts to that no product has zero market share. Similarly, I can show that $\min_{k<j} \frac{\delta_j - \delta_k}{p_j - p_k} = \frac{\delta_j - \delta_{j-1}}{p_j - p_{j-1}}$.

(ii) It is trivial that if $\max_{k>j} \frac{\delta_k - \delta_j}{p_k - p_j} = \frac{\delta_{j+1} - \delta_j}{p_{j+1} - p_j}$, $\min_{k<j} \frac{\delta_j - \delta_k}{p_j - p_k} = \frac{\delta_j - \delta_{j-1}}{p_j - p_{j-1}}$ and $\frac{\delta_j - \delta_{j-1}}{p_j - p_{j-1}} > \frac{\delta_{j+1} - \delta_j}{p_{j+1} - p_j}$, every product has a positive market share. ■

[32] What the outside option is depends on how the market is defined. If the market is defined as the whole CPU market, the outside option is to buy non Intel and AMD products. If the market includes all potential consumers, the outside option includes buying no CPUs at all. In any cases, u_{i0} represents utility of buying neither Intel nor AMD products.

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[Table 1] Summary Statistics: the CPU from 1993Q2 to 2000Q3

Year	Tech†	Speed (in Mhz)			Price (in dollar)			Share⊺		
		Min	Mean	Max	Min	Mean‡	Max	Min	Mean	Max
1993	1	60	63	66	818	888	965	0.0036	0.0063	0.0095
1994	1,2	60	79.7	100	418	764.2	995	0.0013	0.0253	0.0557
1995	1,2,3	60	102	200	158	490.6	1324	0.0016	0.0529	0.1604
1996	2,3	75	143.2	200	106	334.5	1018	0.0011	0.0709	0.1701
1997	2,3,4	90	189.6	333	85	325.1	1981	0.0004	0.0639	0.2022
1998	3,4	166	290.4	450	86	335.2	773	0.0048	0.0861	0.1832
1999	4,5	300	467.1	800	64	275.6	851	0.0037	0.0725	0.1456
2000	4,5	433	615.6	1000	69	285.5	990	0.0005	0.0495	0.1002

†The lithography technology used. 1 refers to 0.8 $m\mu$ (micron) technology, 2 is 0.6 $m\mu$, 3 is 0.35 $m\mu$, 4 is 0.25 $m\mu$ and 5 is 0.18 $m\mu$ technology.

‡The mean price is the average price weighted by quantity.

⊺Share is defined as quantity sold divided by the total number of products sold in the market.

Note–This table presents the summary statistics of key variables. There have been five generations of lithography technology during the sample period. The processing speed increased from 60 Mhz to 1000 Mhz in 8 years. The average price did not go up despite a performance improvement.

[Table 2] Results of the demand estimation

		Log Normal†		Exponential‡	
Characteristics	Speed	2.57* (0.61)	1.58* (0.53)	2.59* (0.60)	1.56* (0.54)
β	$(\text{Speed})^2$	-0.16* (0.04)		-0.16* (0.04)	
	Dtech2ᵀ		0.18 (0.19)		0.11 (0.20)
	Dtech3		1.12* (0.42)		1.14* (0.43)
	Dtech4		0.99 (0.60)		1.09 (0.62)
	Dtech5		-1.15 (1.12)		-0.99 (1.14)
	No_Cache◇	-0.80* (0.23)	-0.27 (0.34)	-0.88* (0.24)	-0.37 (0.35)
Year dummies	Dyear1 (1993)	5.00* (1.13)	5.59* (1.70)	4.54* (1.01)	5.13* (1.59)
γ	Dyear2 (1994)	5.27* (1.20)	5.92* (1.85)	4.82* (1.09)	5.52* (1.76)
	Dyear3 (1995)	5.66* (1.28)	6.24* (1.97)	5.70* (1.25)	6.38* (2.06)
	Dyear4 (1996)	5.93* (1.34)	6.36* (2.05)	6.13* (1.36)	6.69* (2.19)
	Dyear5 (1997)	5.52* (1.24)	5.94* (1.93)	5.56* (1.24)	6.09* (2.02)
	Dyear6 (1998)	3.79* (0.85)	4.34* (1.41)	3.82* (0.84)	4.46* (1.47)
	Dyear7 (1999)	2.75* (0.62)	3.12* (1.03)	2.17* (0.48)	2.58* (0.89)
$\alpha \sim F(\boldsymbol{\theta})$	θ_1	1.81* (0.23)	1.86* (0.32)	1	1
	θ_2	1	1	0.10* (0.02)	0.10* (0.03)
N		321	321	321	321

The constant term is fixed at -6 for normalization, and standard errors are reported in parenthesis.

ᵀDtech2 refers to 0.6 $m\mu$, Dtech3 is 0.35 $m\mu$, Dtech4 is 0.25 $m\mu$ and Dtech5 is 0.18 $m\mu$ technology.

◇No_Cache is a dummy variable for processors without the level 2 cache.

† α is assumed to have the log normal distribution; *i.e.*, $\log(\alpha) \sim N(\theta_1, 1)$.

‡ α is assumed to have the exponential distribution; *i.e.*, $\alpha \sim Gamma(1, \theta_2)$.

*significant at the 5% level.

Note–This table presents a set of regressions in which the dependent variable is product quality, obtained by reversing the market share equation recursively, and the regressors are product characteristics and year dummy variables. The two distributions produce very similar estimates of product characteristics.

[Table 3] Price and semi-elasticity†: $\log(\alpha) \sim N(1.81, 1)$

		DOI$^{\psi}$	t=1	t=2	t=3	t=4	t=5
Pentium 133	price‡	95Q2	935	694	520	321	257
	elasticity		-8.6	-9.3	-118.5	-34.9	-402.4
	semi-elasticity		-0.09	-0.13	-2.28	-1.09	-15.66
Pentium Pro 200	price	95Q4	1324	1018	707	562	525
	elasticity		-9.2	-15.7	-14.0	-31.2	-193.0
	semi-elasticity		-0.07	-0.15	-0.20	-0.56	-3.61
Pentium II 333	price	97Q4	738	722	452	275	181
	elasticity		-102.8	-5.4	-45.8	-31.8	-52.8
	semi-elasticity		-1.39	-0.08	-1.01	-1.16	-2.92
Pentium II 400	price	98Q2	773	536	375	319	200
	elasticity		-6.0	-13.1	-8.9	-19.3	-34.8
	semi-elasticity		-0.08	-0.24	-0.24	-0.61	-1.74
Pentium III 500	price	99Q1	696	566	359	235	173
	elasticity		-6.2	-20.1	-53.4	-133.5	-171.6
	semi-elasticity		-0.09	-0.36	-1.49	-5.68	-9.48
Pentium III 600	price	99Q3	745	503	318	211	183
	elasticity		-7.6	-62.4	-90.0	-233.4	-102.5
	semi-elasticity		-0.10	-1.24	-2.82	-7.87	-4.98

†Elasticities give the percentage change in market share with a percentage change in price. Semi-elasticities give the percentage change in market share with a $10 change in price.

‡Price is in dollar unit.

$^{\psi}$Date of introduction (DOI) is a date when a product is first introduced in the market.

Note–This table presents the time trends of the prices, the price elasticities, and the semi-price elasticities of six CPUs, introduced at different points of time. The prices sharply decline once products are introduced, and the (semi) price elasticities go up as the prices go down. This suggests that firms are likely to set high markups in the early period of product life, in order to recover sunk costs.

[Table 4] Consumer welfare, variable profits, and R&D expenditures: $\log(\alpha) \sim N(1.81, 1)$.

	Welfare1†	Welfare2‡	Profits⊺	R&D⋆	$\frac{\text{Welfare1}}{\text{Welfare1+Profits}}$	$\frac{\text{Welfare2}}{\text{Welfare2+Profits}}$
96Q1	10,738	3,714	3,700	496	0.74	0.50
96Q2	13,523	5,534	3,439	531	0.80	0.62
96Q3	17,486	7,936	3,749	555	0.82	0.68
96Q4	23,793	10,122	4,773	627	0.83	0.68
97Q1	22,538	11,671	4,547	686	0.83	0.72
97Q2	24,017	13,845	5,583	685	0.81	0.71
97Q3	24,191	16,880	3,742	712	0.87	0.82
97Q4	22,343	18,169	3,417	732	0.87	0.84
98Q1	18,184	18,811	3,610	888	0.83	0.84
98Q2	23,536	23,550	4,857	762	0.83	0.83
98Q3	35,297	35,600	6,054	761	0.85	0.85
98Q4	31,304	42,161	4,474	830	0.87	0.90
99Q1	34,134	36,078	3,514	823	0.91	0.91
99Q2	32,565	35,148	3,146	898	0.91	0.92
99Q3	40,923	47,961	4,929	1,331	0.89	0.91
99Q4	44,607	64,143	6,875	1,087	0.87	0.91
00Q1	43,678	84,640	8,941	1,174	0.83	0.90
00Q2	43,825	96,360	8,868	1,148	0.83	0.90
00Q3	40,590	81,610	6,865	1,148	0.86	0.92

Numbers for cw1, cw2, and profits are millions of dollars.

Consumer welfare $\approx \sum_{j=1}^{J} E\left(\frac{1}{\alpha_i}|i \in j\right) q_{jt}\left(\delta_{jt} - \delta_{0t}\right) - \sum_{j=1}^{J} p_{jt} q_{jt}$, where $\log(\alpha) \sim N(1.81, 1)$.

†The value of the outside option is assumed to be zero for all periods.

‡The value of the outside option is recovered, using the continuing products, and is added to $\delta_{jt} - \delta_{0t}$.

⊺$Variable\, profits = \Sigma_j (p_{jt} q_{jt} - mc_{jt} q_{jt})$. The marginal cost is the average manufacturing cost of CPU at maturity, and it is estimated by MicroDesign Resources. However, the cost data are not product-specific, but the average cost of each generation.

⋆R&D expenditures are taken from Wharton Research Data Services.

Note–This table compares consumer welfare with firms' variable profits and R&D expenditures. Two different sets of numbers are presented for consumer welfare. The increase of welfare in the late 1990s coincides with a higher rate of innovation in the semiconductor industry. This shortened the interval between new products entering the market, and the welfare trend reflects consumer benefits from this more frequent entry of new products. The table also shows that consumer welfare consists of approximately 90% of total social surplus in the late 1990's, which suggests that consumers gain much more than firms from more frequent innovation.

[Table 5] One random coefficient vs. two random coefficients: $\log(\alpha) \sim N(\theta, 1)$

		Vertical		Pure Characteristics	
β	Speed	2.57* (0.61)	1.58* (0.53)	3.48* (1.76)	2.00 (1.54)
	$(\text{Speed})^2$	-0.16* (0.04)		-0.20 (0.11)	
	Dtech2†		0.18 (0.19)		-0.22 (0.28)
	Dtech3		1.12* (0.42)		1.99 (1.12)
	Dtech4		0.99 (0.60)		2.91* (1.35)
	Dtech5		-1.15 (1.12)		0.47 (1.59)
$\beta_{is} \sim N(\beta_s, \sigma)$	No_Cache‡ (β_s)	-0.80* (0.23)	-0.27 (0.34)	-2.93* (1.24)	-2.25* (0.76)
	σ	0	0	2.46* (1.15)	2.03 (1.52)
γ	Dyear1 (1993)	5.00* (1.13)	5.59* (1.70)	4.97 (2.55)	5.89 (5.10)
	Dyear2 (1994)	5.27* (1.20)	5.92* (1.85)	5.70* (2.81)	7.02 (5.64)
	Dyear3 (1995)	5.66* (1.28)	6.24* (1.97)	6.72* (3.17)	7.94 (6.08)
	Dyear4 (1996)	5.93* (1.34)	6.36* (2.05)	7.74* (3.48)	8.59 (6.39)
	Dyear5 (1997)	5.52* (1.24)	5.94* (1.93)	7.46* (3.14)	8.17 (6.02)
	Dyear6 (1998)	3.79* (0.85)	4.34* (1.41)	5.17* (2.02)	5.85 (4.31)
	Dyear7 (1999)	2.75* (0.62)	3.12* (1.03)	5.33* (1.50)	5.54* (1.54)
$\log(\alpha) \sim N(\theta_1, 1)$	θ_1	1.81* (0.23)	1.86* (0.32)	2.46* (0.41)	2.53* (0.55)
N		321		321	

The constant term is fixed at -6 for normalization.

†Dtech2 refers to 0.6 $m\mu$, Dtech3 is 0.35 $m\mu$, Dtech4 is 0.25 $m\mu$ and Dtech5 is 0.18 $m\mu$ technology.

‡No_Cache is a dummy variable for processors without the level 2 cache.

*significant at the 5% level.

Standard errors are reported in parenthesis.

Note–This table compares estimation results of the two random coefficient model (the general pure characteristics model) with the one random coefficient model (the vertical model.) In addition to the random coefficient on the price variable, another random coefficient is put on the dummy variable for not having the L2 cache. The estimates of the mean and the variance of the additional random coefficient are statistically significant in the first specification. All estimates on product characteristics in the two random coefficient model are higher (except for the dummy variable for the second generation technology) than the vertical model.

[Table 6] Effects of quality changes on prices in Bertrand Nash equilibrium.

	Firm 1		Firm 2		Firm 1		Firm 2	
	ω_{1f}	ω_{1n}	ω_{2f}	ω_{2n}	p_{1f}	p_{1n}	p_{2f}	p_{2n}
case 1	3.0	1.5	1.0	0.5	**4.600**	1.150	0.428	0.205
	3.0	1.5	2.0	0.5	**2.600**	0.301	0.641	0.058
	3.0	1.5	2.5	0.5	**1.600**	0.290	0.803	0.056
case 2	3.0	2.5	1.0	0.5	**4.600**	3.417	0.691	0.336
	3.0	2.5	1.5	0.5	**3.600**	2.416	0.810	0.251
	3.0	2.5	2.0	0.5	**2.600**	1.417	0.730	0.156
case 3	3.5	1.5	1.0	0.5	**5.816**	1.150	0.428	0.205
	3.5	1.5	2.0	0.5	**3.817**	0.317	0.686	0.061
	3.5	1.5	2.5	0.5	**2.817**	0.338	0.989	0.064
	3.5	1.5	3.0	0.5	**1.817**	0.300	1.043	0.058
case 4	3.5	2.5	1.0	0.5	**5.817**	3.417	0.691	0.336
	3.5	2.5	1.5	0.5	**4.817**	2.417	0.810	0.251
	3.5	2.5	2.0	0.5	**3.817**	1.417	0.730	0.156
	3.5	2.5	3.0	0.5	**1.817**	0.577	0.894	0.066

Price is in a thousand dollar unit.

The first subscript identifies firms that produce products and f in the second subscript indicates a product is the frontier product and n indicates a product is the non-frontier product.

Note–This table presents the simulation results of a multiproduct duopoly market. In each case only ω_{2f} varies while qualities of other three products are fixed. ω is a quality level of product and p is a profit maximizing price. The results show that the price is more sensitive to the quality difference with the rival product than to its own quality level.

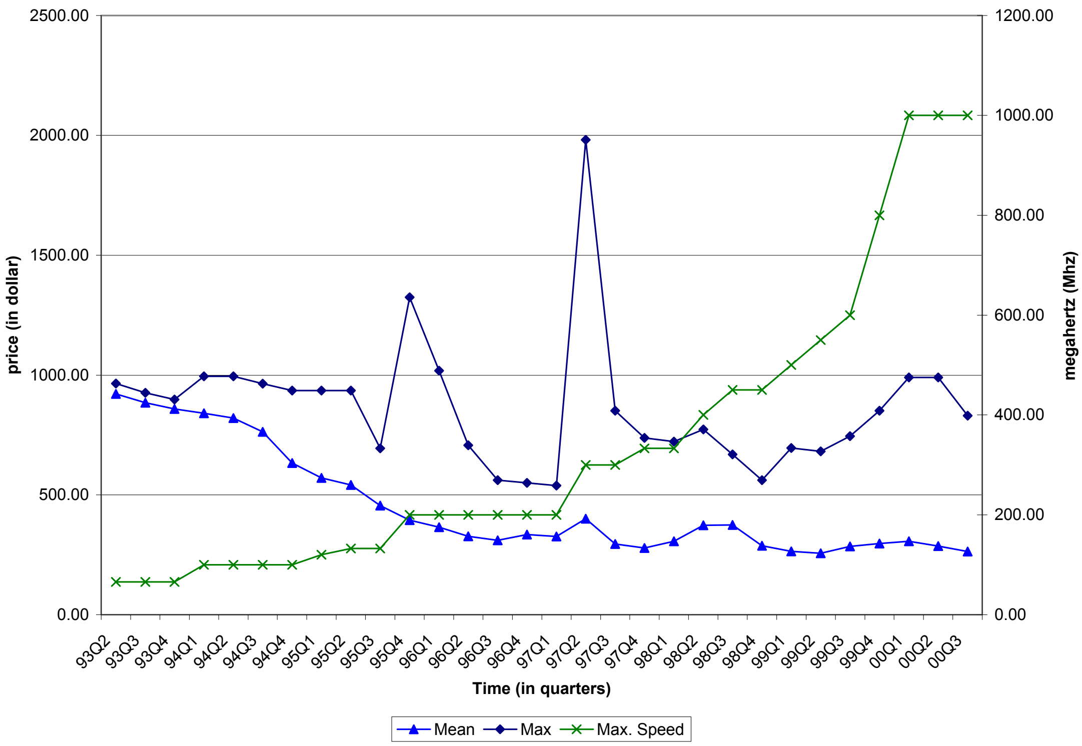

Figure 1: The price trends and the maximum speed, from 1993 to 2000

Source: MicroDesign Resources.
The prices are in dollars and the maximum speed is in megahertz.

Note–The figures shows time trends of the maximum (Max) and the mean price (Mean) of CPUs with the maximum processing speed (Max. Speed) from the second quarter of 1993 to the third quarter of 2000. The figure does not include 386 and 486 processors and the mean price is the quantity weighted average price. It is shown that the average price does not go up despite a drastic performance improvement in the late 1990s.

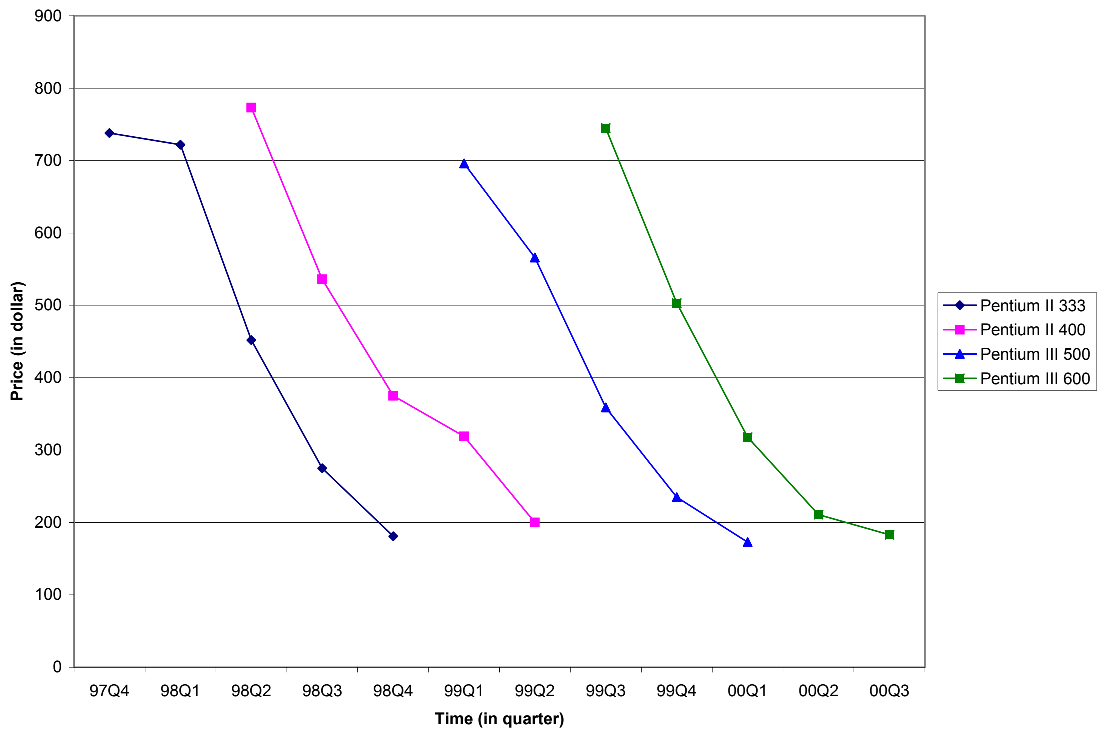

Figure 2: Price trend of individual products.

Source: MicroDesign Resources.

Note–The figure shows price trends of four different CPUs. From the left: Intel Pentium II 333 Mhz processor, Intel Pentium II 400 Mhz processor, Intel Pentium III 500 Mhz processor and Intel Pentium III 600 Mhz processor. It is shown that the prices follow a very similar path, despite differences in the processor speed.

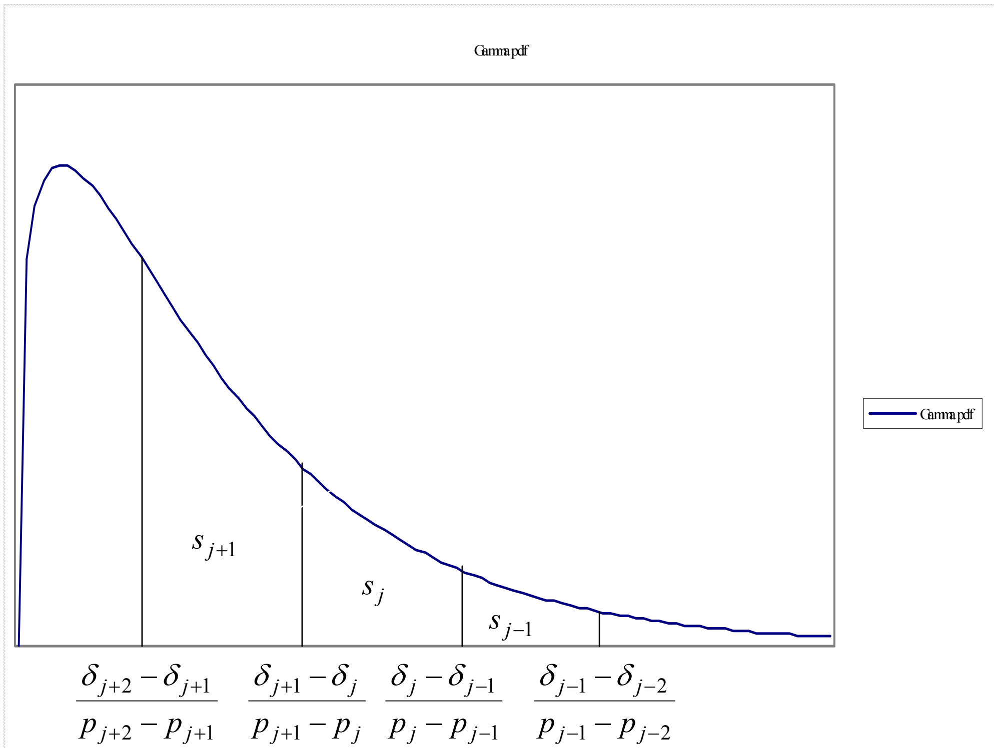

Figure 3: Market shares of three adjacent products for $\alpha \sim Gamma\,(\theta_1, \theta_2)$.

Note–The figure depicts market shares of three products that are located next to each other. The distribution of consumers' valuation is assumed to be the gamma distribution. It shows that the ratio of a quality difference to a price difference between two adjacent products determines market shares.

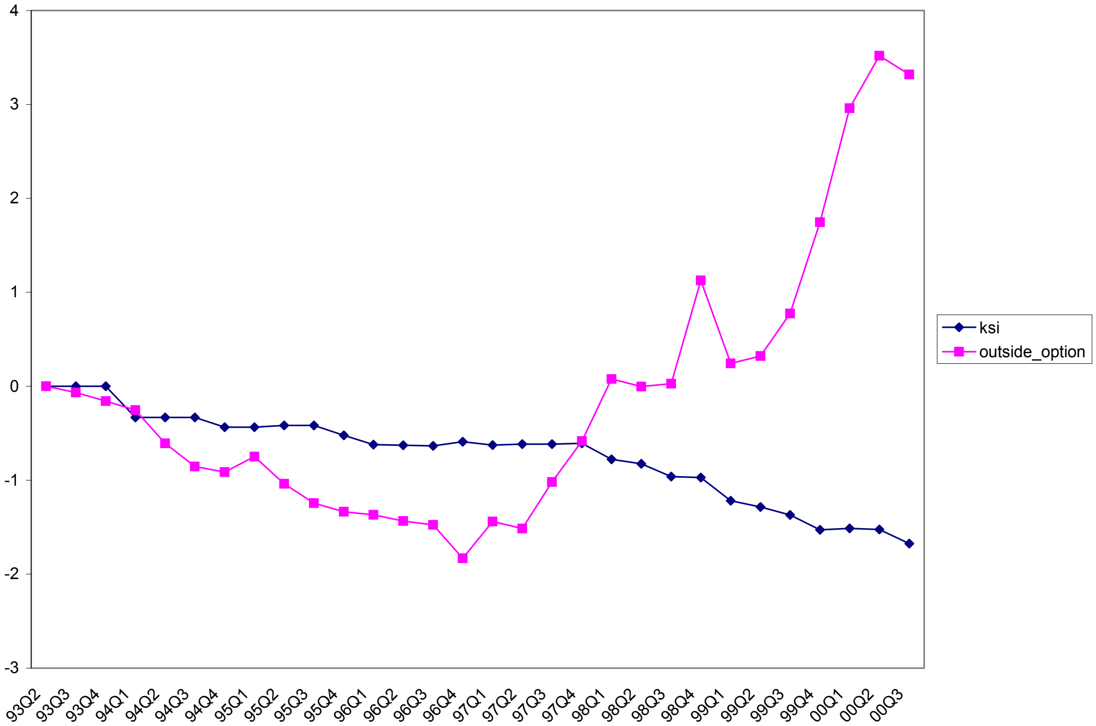

Figure 4: The outside option and unobservable characteristics

Note–The figure shows the time trends of the outside option (outside_option) and unobservable characteristics (ksi). Based on the assumption is that, on average, the unobservable characteristics of continuing products do not change over time, the value of the outside option is separated from that of unobservable characteristics.

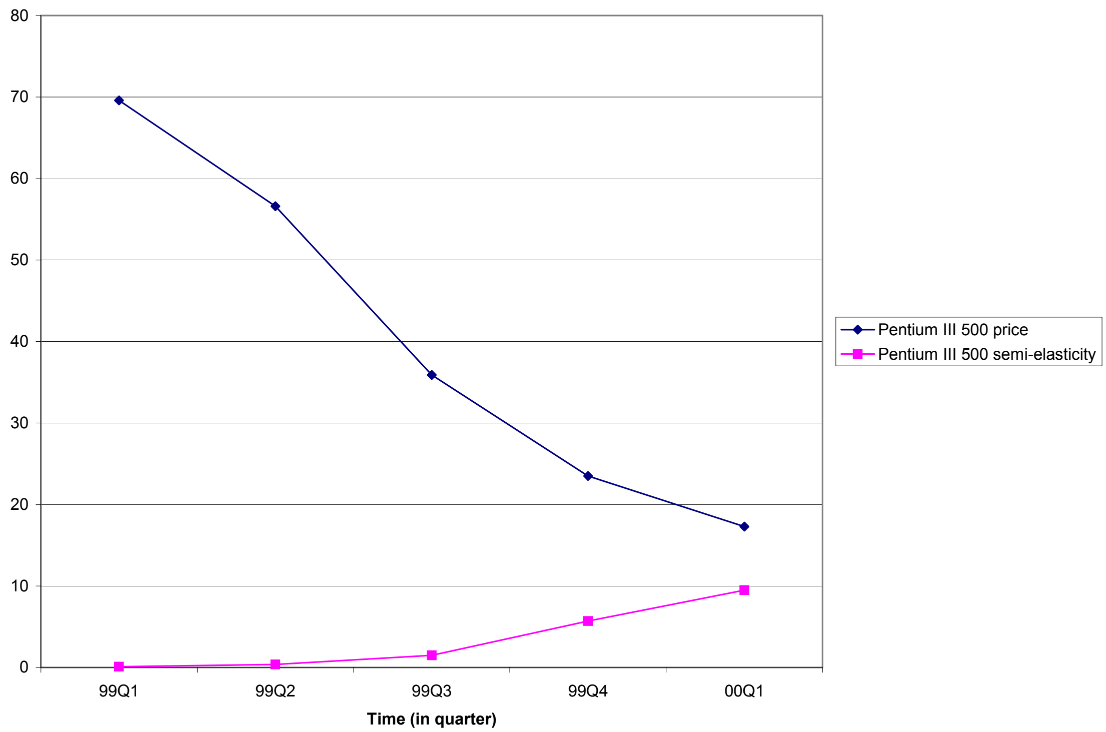

Figure 5: Price and Semi-elasticity of Pentium III 500Mhz processor.

Price is in a ten dollar unit.

Note–The figure shows price and semi-elasticity of Pentium III 500Mhz processor CPU. Semi-elasticity is the percentage change in market share for a $10 decrease in price. As the price falls, the semi-elasticity goes up, which suggests that firms set high markups in the early period of product life.

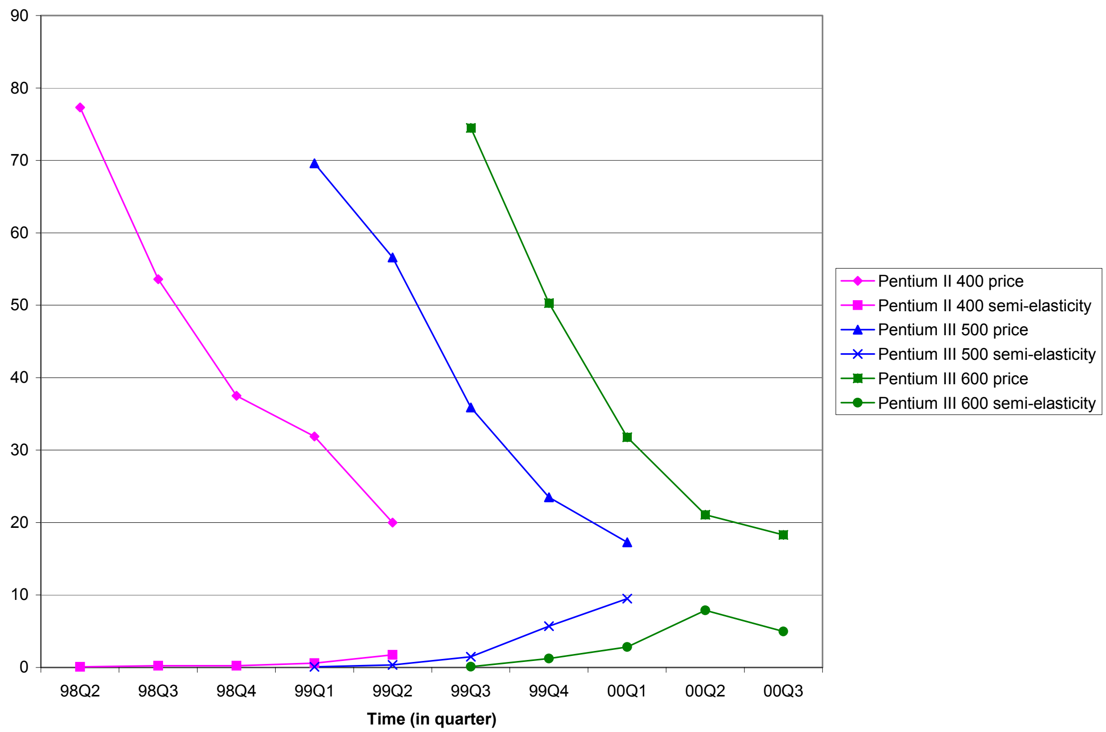

Figure 6: Comparison of Price and Semi-elasticity.

Price is in a ten dollar unit

Note–The figure compares price and semi-elasticity of three different CPUs. Semi-elasticity is the percentage change in market share for a $10 decrease in price. It is shown that the semi-elasticities as well as the prices follow similar paths.

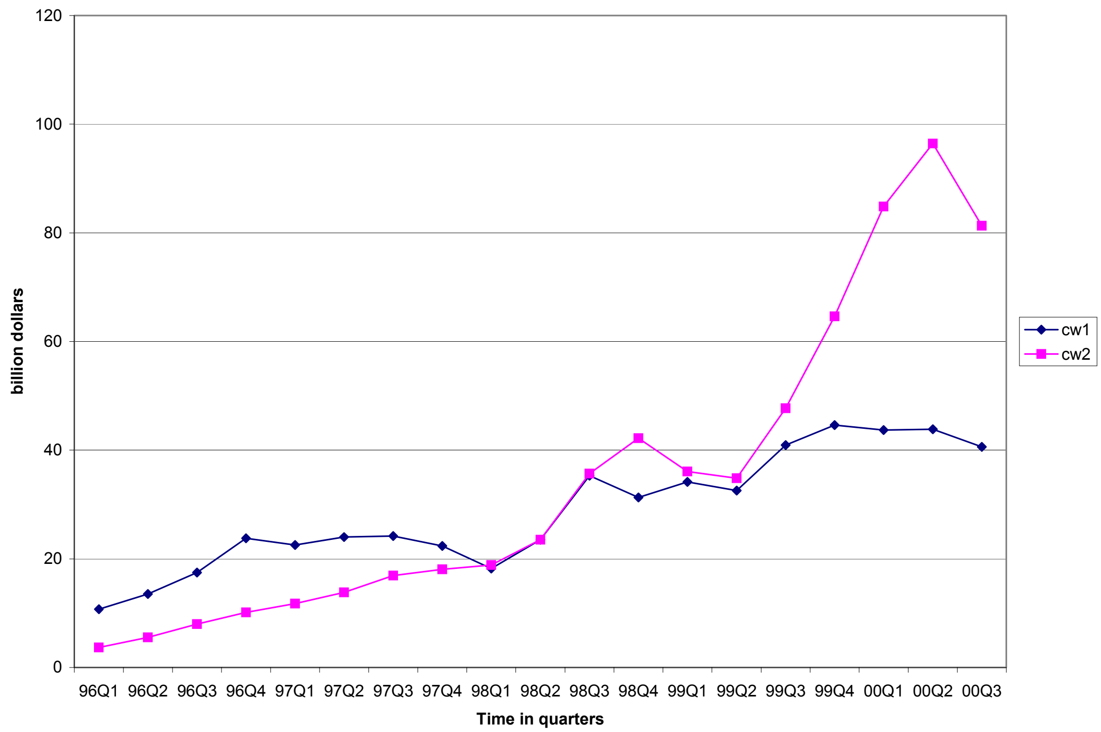

Figure 7: Consumer welfare from 1996 to 2000

Welfare is in billion dollar units.

Note–The figure illustrates the time trends of consumer welfare from 1996 to 2000. Consumer welfare is calculated as $CW_t \approx \sum_{j=1}^{J} E\left(\frac{1}{\alpha_i}|i \in j\right) q_{jt}\left(\delta_{jt} - \delta_{0t}\right) - \sum_{j=1}^{J} p_{jt} q_{jt}$ where $\log(\alpha) \sim N(1.81, 1)$. cw1 is consumer welfare when the value of the outside option is assumed to be zero for all periods. cw2 is consumer welfare when the value of the outside option is recovered, using the continuing products, and is added to $\delta_{jt} - \delta_{0t}$. Alternatively, cw1 can be interpreted as the consumers' relative gains of buying Intel and AMD products, compared with buying other products.

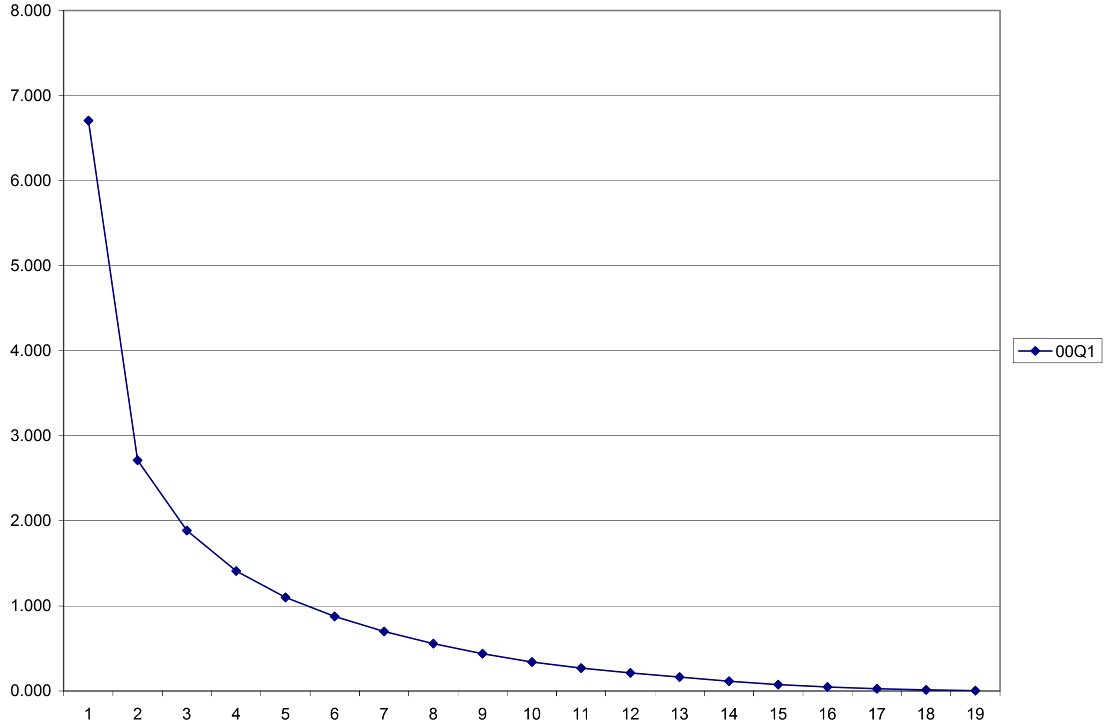

Figure 8: The average consumer welfare in the first quarter of 2000

Note–The figure shows the average welfare gain of each group of consumers. Consumers in the left end are those who bought just released Pentium III 1 Ghz processors and they gain \$6,700 on average. Consumers in the second group, *i.e.* those who bought Pentium III 800 Mhz processors, gain \$2,700 on average. From the sixth group on, the gain falls below \$1,000, and the groups in the far low end gain less than \$100.

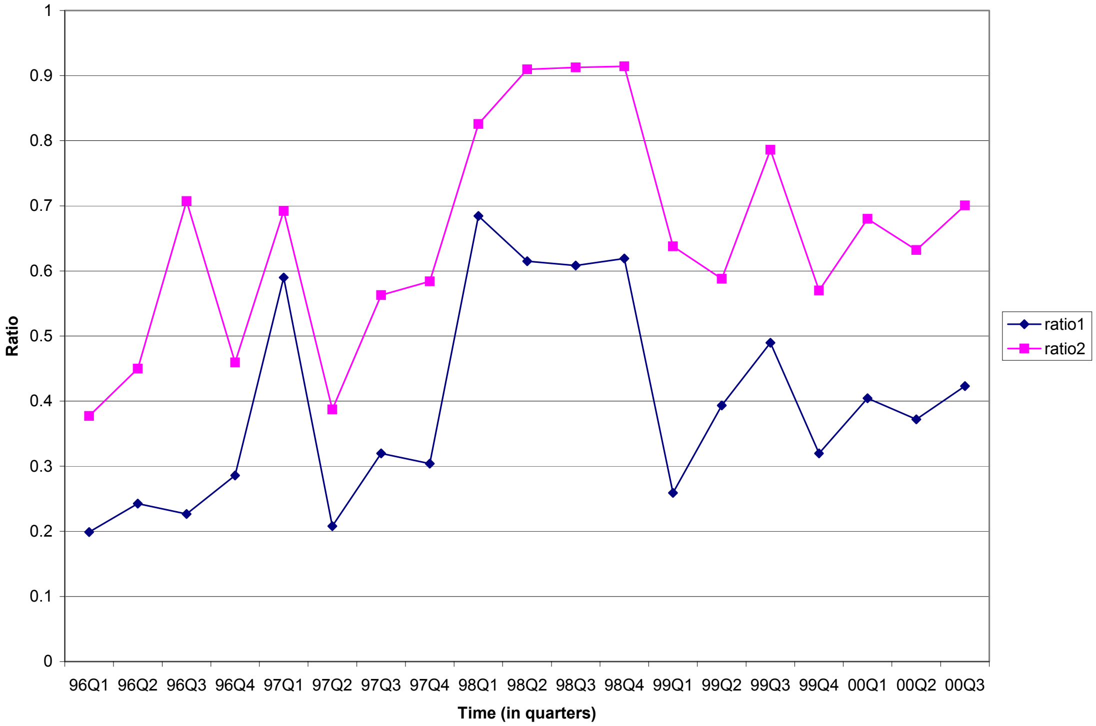

Figure 9: The contribution of high end products to consumer welfare

Note–The figure shows the fractions of consumer welfare generated by the high end products. Ratio1 is a fraction of consumer welfare generated by the highest quality product, and ratio2 is a fraction of consumer welfare generated by the three highest quality products. One should note that exceptionally high ratios in 1998 are due to the relatively small number of products in the market in that year.

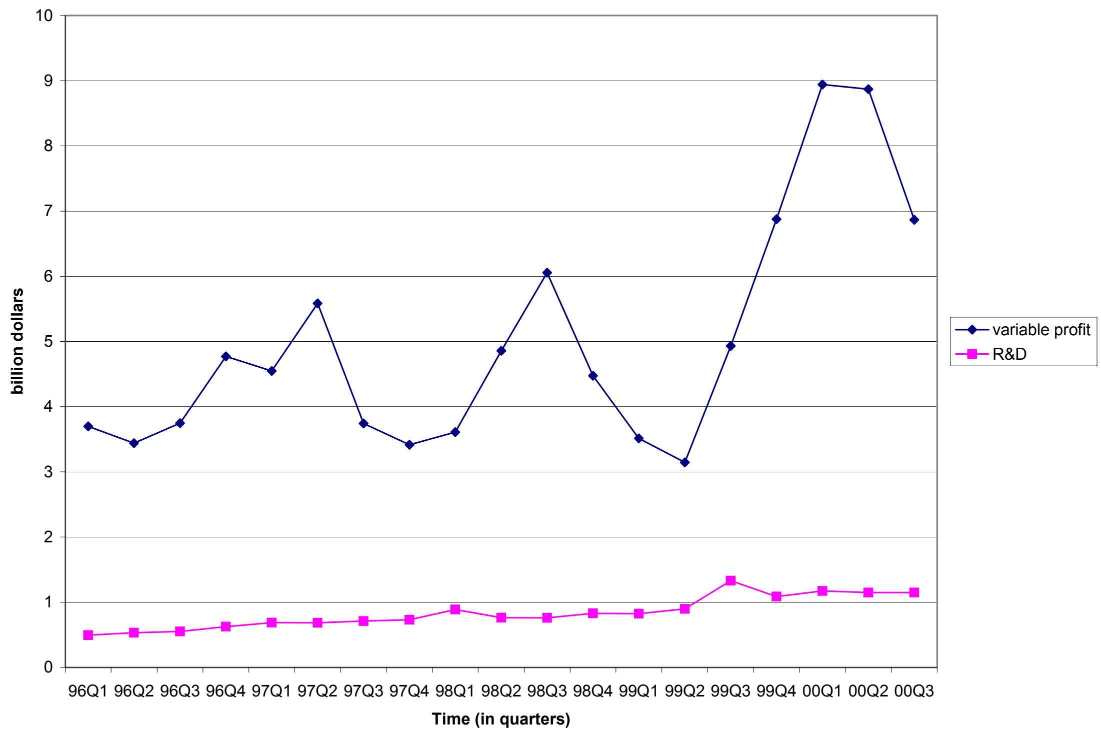

Figure 10: The time trends of variable profits and R&D expenditures.

Numbers are in billion dollar units.

R&D expenditures are taken from Wharton Research Data Services.

Note–The figure shows the time trends of firms' variable profits and R&D expenditures. Each firm's variable profit in each period is defined as $\pi_t = \sum_{j=1}^{J} (p_{jt} - mc_{jt})\, q_{jt}$. The marginal cost is the average manufacturing cost of CPU at maturity, and it is estimated by MicroDesign Resources. However, the cost data are not product-specific, but the average cost of each generation.

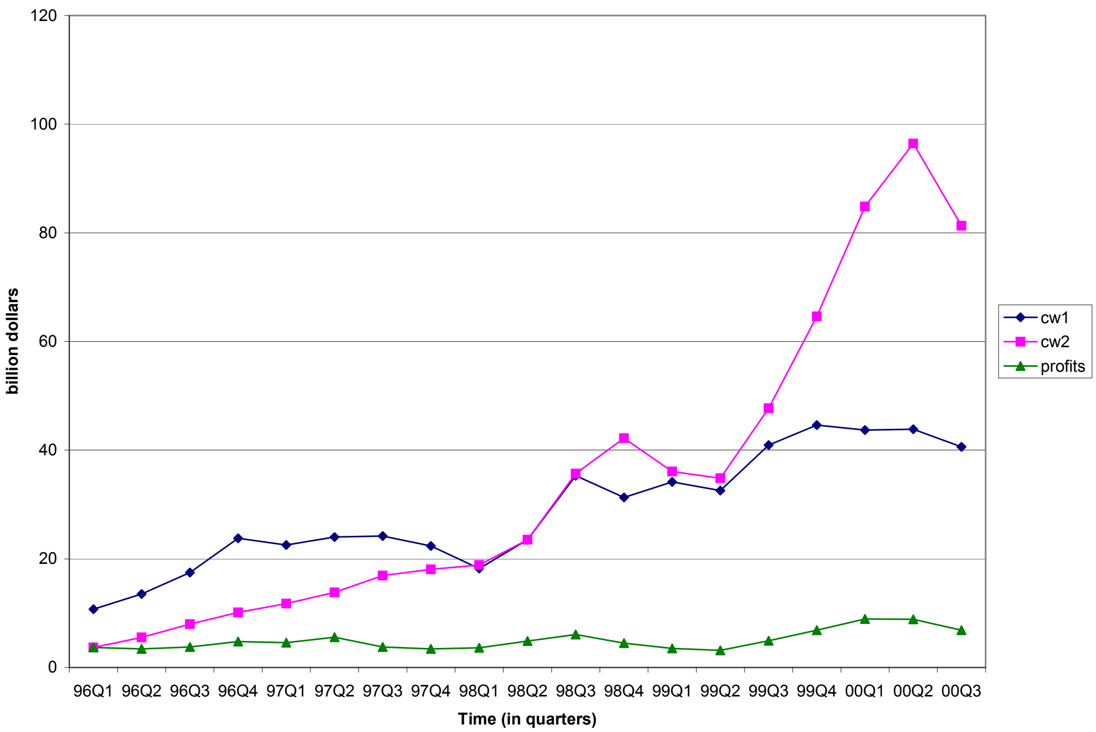

Figure 11: Consumer welfare and firms' profits

Numbers are billions of dollars.

Note–The figure compares consumer welfare and firms' variable profits from the second quarter of 1996 to the third quarter of 2000. The consumer welfare is calculated as $CW_t \approx \sum_{j=1}^{J} E\left(\frac{1}{\alpha_i}|i \in j\right) q_{jt}\left(\delta_{jt} - \delta_{0t}\right) - \sum_{j=1}^{J} p_{jt}q_{jt}$, where $\log(\alpha) \sim N(1.81, 1)$. Variable profit in each period is defined as $\pi_t = \sum_{j=1}^{J}\left(p_{jt} - mc_{jt}\right) q_{jt}$. The marginal cost is the average manufacturing cost of CPU at maturity, and it is estimated by MicroDesign Resources. However, the cost data are not product-specific, but the average cost of each generation.

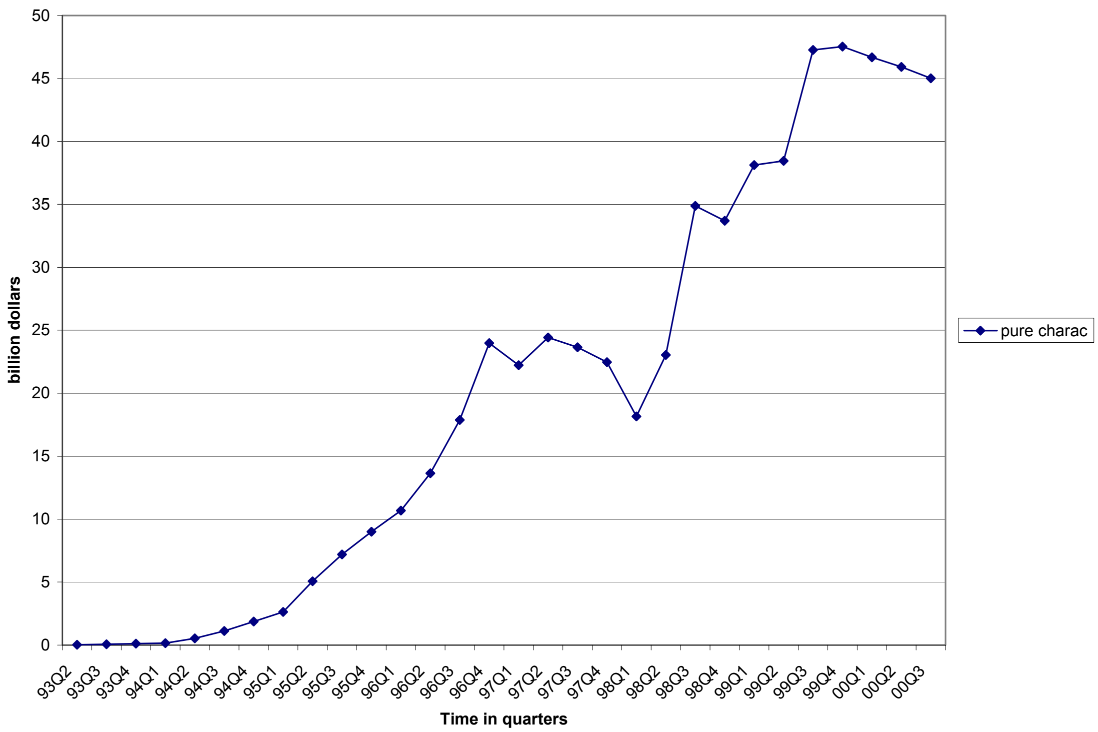

Figure 12: Consumer welfare in the pure characteristics model.

Note–The figure depicts consumer welfare in the pure characteristics model. In addition to the random coefficient on the price variable, another random coefficient is put on the dummy variable for not having the L2 cache. The consumer welfare for the pure characteristics model is calculated as

$$cw_t \approx \sum_{j=1}^{J} q_{jt}(E(\frac{1}{\alpha_i}|i \in j)(\delta_{jt} - \delta_{0t}) + E(\frac{1}{\alpha_i}|\upsilon_i, i \in j)E(\upsilon_i|i \in j)x_{sjt}\widehat{\sigma} - p_{jt}),$$

where $\log(\alpha) \sim N(2.46, 1)$, $\upsilon_i \sim N(0, 1)$, and $\widehat{\sigma} = 2.46$.

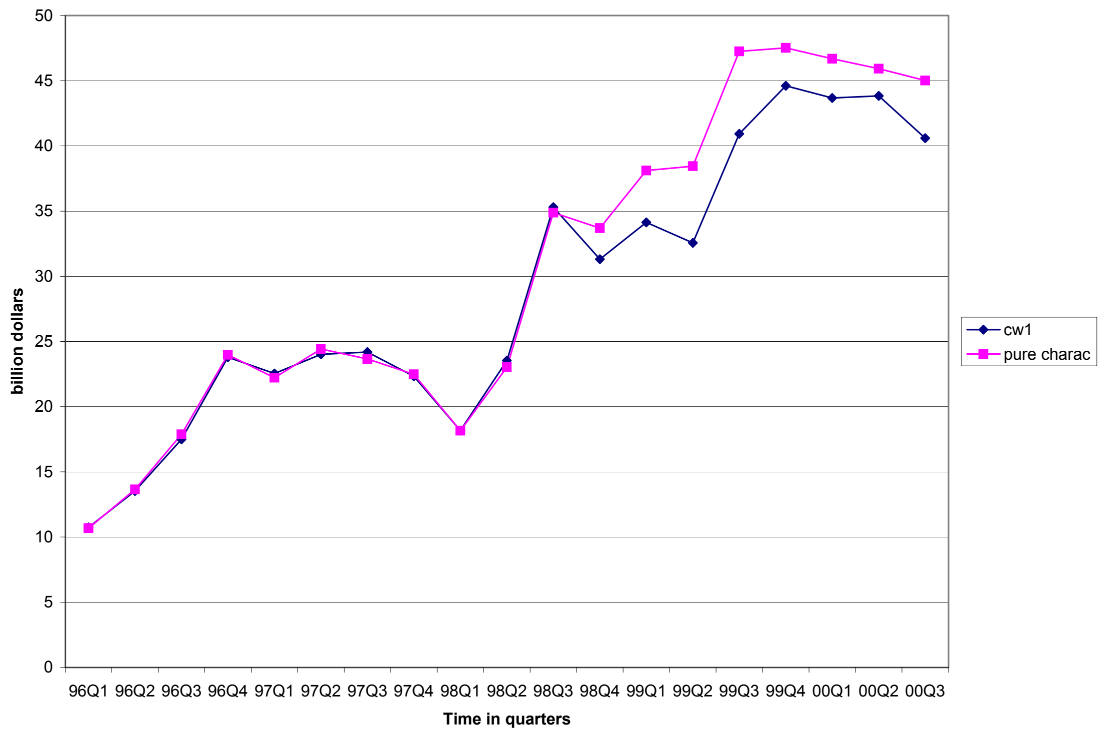

Figure 13: Consuer welfare: one vs. two random coefficients

Note–The figure compares consumer welfare for two different demand models; the vertical model (one random coefficient) and the pure characteristics model (two random coefficients.) In the pure characteristics demand model, another random coefficient is put on the dummy variable for not having the L2 cache, in addition to the random coefficient on the price variable. The two graphs are almost identical until the Celeron CPU, the CPU without the L2 cache, was introduced in the third quarter of 1998.

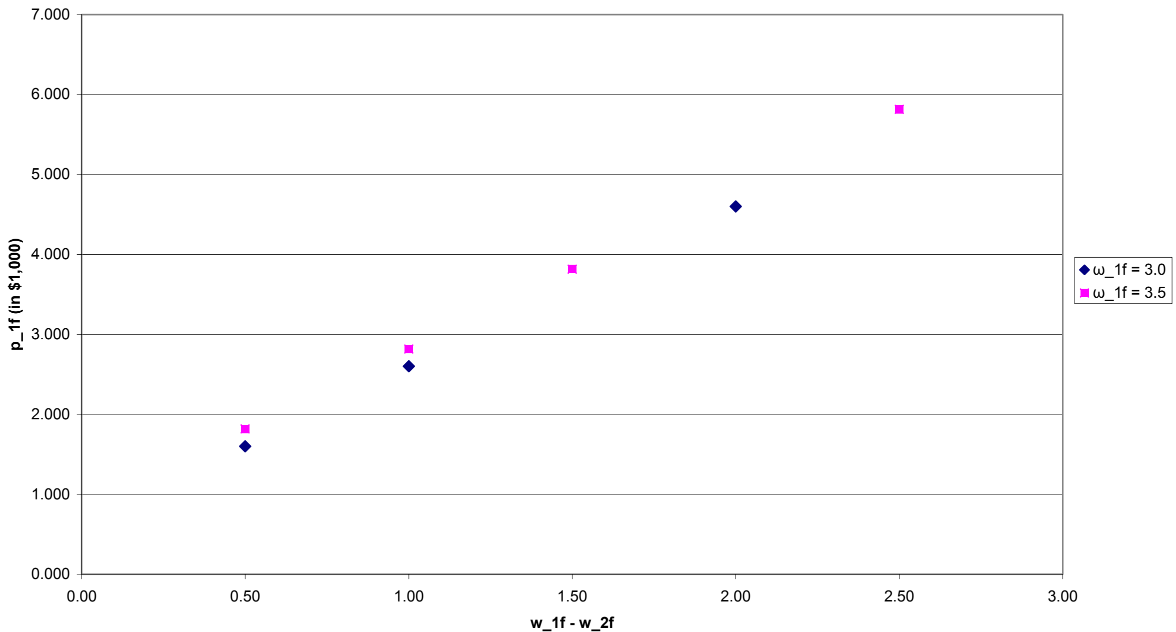

Figure 14: An effect of quality difference on price.

Note–The figure shows an effect of quality difference, *i.e.* $\omega_{1f} - \omega_{2f}$, on price of the highest quality product, *i.e.* p_{1f}. The x-axis is a quality difference between the frontier product of firm 1 and the frontier product of firm 2 and the y-axis is a price of the frontier product of firm 1. ω_{1n} and ω_{2n} are fixed at 1.5 and 0.5 respectively. The square mark represents a price of the frontier product of firm 1 when its quality is 3.5 and the diamond shape mark represents a price of the frontier product of firm 1 when its quality is 3.0. The figure shows that given the quality difference there is a small change in p_{1f} when the quality goes up from 3.0 to 3.5 (comparing the square mark with the diamond shape mark at x=0.5 or x=1.0.) but that changes in the quality difference induce relatively big changes in p_{1f} (comparing the square mark (the diamond shape mark) at x=0.5 with the square mark (the diamond shape mark) at x=1.0.)