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AN HEDONIC PRICE ANALYSIS OF PDAs

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ABSTRACT

We compute quality-adjusted price indexes for Personal Digital Assistants (PDAs) for the period 1999-2004, using data on prices and characteristics of 203 models sold by 12 manufacturers. The PDA market is growing in size, it is technologically dynamic with very substantial changes in measured characteristics over time, and it has experienced rapid rates of product introduction. Hedonic regressions consistently show prices to be positively related to processor performance, RAM memory, permanent storage capacity, and battery life, as well as several measures of screen size and quality. Features such as networking, biometric identification, camera, and cellphone capability are also positively associated with price. Hedonic price indexes implied by these regressions decline at an AAGR of 21.1% to 25.6% per year during this period. A matched model price index computed from a subset of observations declines at 18.75% per year. Though these PDA rates of price decline are lower than have been estimated for desktop and laptop PCs, consumers in this "ultra-portable" segment of the computer market appear to have enjoyed substantial welfare gains over the past five years.

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I. Introduction

Personal digital assistants ("PDAs") have become an increasingly significant segment of the market for personal computing devices, accounting for almost 6% of worldwide units shipped in 2003. Like other personal computing devices, PDAs have undergone rapid technological change in recent decades. Since the introduction of the Apple Newton in 1993, both the computational power and the storage capacity of PDAs have grown by several orders of magnitude, and the variety and functionality of peripherals and interface technology have increased dramatically. Although the engineering design and marketing of PDAs have consistently emphasized simple "organizer" functions (calendar, address book, memopad, etc.) PDAs are now capable of running complex software applications and storing large amounts of data.

Leading edge PDA devices now have computational "horsepower" and storage equivalent to the high-end laptop and desktop PCs of the mid 1990s, high resolution color screens that rival those of standard PCs in terms of resolution and the faithfulness of color reproduction, and high-bandwidth network connectivity. Notwithstanding these dramatic improvements in performance and capacity over the past decade, nominal prices for these devices have been flat, or have even trended downwards. Thus, like their less portable cousins, PDAs have experienced very large declines in quality-adjusted prices – implying substantial gains in welfare for consumers who value portable computing.

In this paper we document changes in prices and characteristics of PDAs over time, and construct a preliminary quality-adjusted price index. We begin with a summary of the historical development of PDA technology, then briefly review the literature on measuring price change in computing platforms, emphasizing that focusing on portable computers. Next we describe the data on PDAs used in this study, and the trends evident in this marketplace. We conclude with an analysis of quality-adjusted price change in this market, and the construction of a variety of preliminary hedonic price indexes for PDAs.

II. A Short History of PDAs

Driven by innovation in microprocessors, storage and display technology, PDAs have evolved in close parallel with desktop and laptop computers. Although the commonly accepted definition of a PDA has evolved somewhat over time, most PDA designs have been inspired by the vision of a small, light, easily transportable "stripped down" computing device. This focus on portability raises unique design and engineering challenges. "On-the-go" computing requires highly miniaturized, tightly integrated, custom components, with a premium on robustness and low power consumption. Even more than with laptops, PDA designs embody difficult trade-offs between incompatible user-valued characteristics (speed/storage capacity/screen size versus size/weight/battery life) and engineering constraints. Polsson (2002) provides a useful chronology of the development of PDA technology and products. Here we offer a brief summary of the evolution of PDA technology and the PDA market.

Current PDAs have their roots in the small, "pocket" or "palmtop computers" of the early 1980s such as the Radio Shack TRS-80 Hand Held Computer and the Sharp PC-1500 Hand Held Personal Computer. These relatively large early machines were made by computer manufacturers and were meant to be very small personal computers. These machines typically had QWERTY keyboards, minimal black-and-white displays (24 characters wide and a few lines high) and very modest processing power, but attempted to provide PC-type applications.

An alternate vision of handheld computing emerged in the early 1990s, with a smaller class of machines dubbed "pen-based computers." These devices lacked a keyboard, relying instead for user input on touch-sensitive screens and the ability to interpret users' handwriting, along with small numbers of function-specific buttons. Marketing of these products emphasized mobile access to information, and the novelty of the pen-based interface, two key features of current PDAs. The Apple Newton is commonly identified as the "first PDA," with the term "personal digital assistant" coined by Apple CEO John Scully in 1992, just prior to the release of the Newton in 1993. Other notable pen-based computers included the Casio Zoomer (1993) and Sharp ExpertPad (1993). Yet another vision of handheld computers was put forward by telecommunications companies, who visualized PDAs as "mobile communicators" that provided portable wireless connectivity. Examples of early communicators included the Eo Personal Communicator (1992), the Sony MagicLink (1994) and the Motorola Envoy (1995).

Until 1996, the handheld market was highly fragmented, with incompatible competing platforms designed to solve different problems. The introduction of Palm Computing's PalmPilot in 1996, however, caused the PDA market to settle on a de facto definition of a PDA as a "connected organizer" whose essential characteristics consisted of providing organizer capabilities that synchronized with a PC (Allen, 1999). Other manufacturers such as Hewlett-Packard, Sharp, and Franklin quickly began producing connected organizers, and within two years, nearly all hand-held computers provided this functionality. Palm (since acquired by 3Com) licensed the Palm operating system to other manufacturers, and the Palm OS quickly became the dominant operating system in the PDA market, especially in the U.S., where 70% of PDAs sold in 2002 used the Palm OS (Kort 2003).

However, the handheld market is highly dynamic, and the dominance of the Palm "connected organizer" platform in the late 1990s and early 2000s has spurred innovation in both the "palmtop computer" and "mobile communicator" platforms. The steadily rising share of Windows-CE based PDAs signals a renewed focus on the conception of a PDA as a palm-sized version of "standard" computers that runs very similar software applications. While all Windows-based PDAs have the abilities of a connected organizer, they frequently provide other PC-like capabilities and applications, such as email, spreadsheets, word processors, and increasingly sophisticated games. Though unit shipments of Palm-OS based PDAs are currently slightly higher than those of Windows based PDAs (as of Q2 2004), Windows based PDAs outsell Palm based devices in dollar terms due to their higher average price.

The "mobile communicator" began to evolve into the "smart phone" in the late 1990s, with the release of the first telephone with the capabilities of a connected organizer, the Nokia 9000i communicator, in 1997. A growing number of manufacturers – including Kyocera, Handspring, and Research in Motion – offer smart phones based on the Palm OS, Windows CE, Symbian, and other proprietary operating systems. Although smart phones are not currently competitive with PDAs in terms of price, battery life, and other factors, the smart phone platform is expected to make significant inroads against PDAs from 2004 onward.

The functionality of all platforms of handheld computers continues to evolve rapidly, with steady increases in computing and storage power anticipated to continue indefinitely. Additional new functionality, such as a digital camera, 802.11b wireless LAN (WiFi) networking, Bluetooth networking, MP3 player capability, and biometric security (fingerprint reader) continues to be added. A recent new category of features is that which relies on location information, such as atlas software or global positioning system (GPS) modules for PDAs, such as the Magellan system for the Palm series of PDAs.

III. Measuring Computer Prices

Ongoing technological innovation has led economists to study price and quality change in computing technology since the 1960s – pioneering studies include Knight (1966) and Chow (1967). Over the subsequent decades, research has examined mainframe computer processors, peripheral equipment, personal computers (PCs), and portable or "laptop" PCs.[1] This research has focused on quantifying the rate of change in the price-performance ratio of computing technology through the construction of "quality-adjusted" price indexes. The production and consumption of computing technology are now so pervasive in the economy that computer price indexes have measurable impacts on key macroeconomic statistics such as the consumer price index (CPI), real GDP, and productivity growth rates.[2]

The traditional approach to measuring price variations in the face of quality change is the matched-model technique. As with all approaches, observations on the prices and attributes of a number of goods are made at periodic intervals. When the same "model" (i.e., a product having exactly the same attributes) appears in two time periods, any difference in the prices for the model must be due to pure price change, as there is no quality change. Price indexes are constructed using the ratio of prices of the models that are "matched" across time periods. However, product markets characterized by rapid

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[1] This literature is reviewed more thoroughly in Berndt (1991), Triplett (1989), Berndt and Rappaport (2001), Triplett (2001), and Chwelos (2003).
[2] Landefeld and Grimm (2000).

technological change have a high frequency of the introduction of new models and the discontinuation of old models; in this setting, there will be relatively few “matches” across time periods, and the matched model method becomes subject to a number of biases due to non-random entry and exit of models. One important source of this bias is sample selectivity induced by the exiting models: discontinued models will tend to be those for which consumers’ valuations have fallen the most – see Pakes (2001).

The most common approach to dealing with quality change in economics is the use of an hedonic function. The hedonic hypothesis proposes that a heterogeneous good can be treated as an aggregation of homogenous attributes, i.e.,

$$P = h(c) \qquad (1)$$

where P is an n-element vector of prices of models of heterogeneous goods, c is a $k \times n$ matrix of (homogeneous) attributes, and $h(c)$ is the hedonic function. Therefore, a complex good such as an automobile can be treated as a collection of simple attributes such as horsepower, fuel economy, number of seats, etc.

The use of hedonic methods dates back at least to Waugh (1928), who undertook empirical work relating the price of asparagus bundles to their attributes (length, color, number of stalks). The term hedonic was coined in Court (1939), in work addressing automobiles. Griliches (1961) brought hedonic methods into the mainstream economic measurement literature by updating Court’s work on automobiles, and considerably extending hedonic methods.

Rosen (1974) showed that, in general, the hedonic function is an envelope function of the users’ value function and the producers’ cost function. As with any envelope function, the form of the hedonic function is independent of the forms of the user preferences or producer costs underlying it; instead, it is determined by the distribution of buyers’ preferences and sellers’ costs and strategic choices.

Triplett (1983, 1987) took the necessary step of extending index number theory from goods space to characteristics space. He demonstrated that an hedonic price index can be thought of as an approximation of an exact characteristics subindex provided that the utility function is separable between the attributes of the heterogeneous good and the quantities of other, homogeneous goods. Triplett suggests three criteria for evaluating the characteristics to be included as explanatory variables in an hedonic multivariate regression specification:

1. they are homogeneous economic variables;
2. they are building blocks from which heterogeneous goods are created; and
3. they are valued by both buyers and sellers.

In work on personal computers, a large variety of characteristics have been included in hedonic regressions; however, nearly all researchers have attempted to operationalize the performance (or "speed") along with the quantity of secondary storage. Performance has traditionally been measured using a variety of technical proxies (e.g., processor clock speed in MHz, processor word length) or, more recently, with performance benchmarks, as in Chwelos (1999) and Nordhaus (2001).

Recent theoretical work continues to explore the theory underlying hedonic functions and their use in constructing price indexes. Pakes (2001) generalizes the interpretation of the hedonic function to allow for interpersonal differences in utility over characteristics, as well as imperfect product market competition, thereby noting that the observed hedonic function is the result of a complex market equilibrium. Thus we should not apply either a consumer willingness-to-pay or producer marginal cost interpretation to the estimated coefficients. Rather, he argues for the use of an hedonic function in constructing "proper" price indexes, which provide an upper bound on the compensating variation required to compensate consumers for a change in prices independent of the form of the utility function. In this context, the estimated hedonic surface is simply used to impute the prices of exiting goods, without regard to *how* the surface is shaped (i.e., the signs and magnitudes of the estimated coefficients).

Diewert (2001) provides an interpretation of the hedonic function based on consumer theory, ignoring the producer side of the market. Using a representative agent approach (i.e., all consumers have the same utility for characteristics), he derives a variety of functional forms, and notes which of these are consistent with consumer theory yet are sufficiently flexible to incorporate new characteristics. While there is no one preferred functional form, he notes that the linear hedonic function is not consistent with homothetic preferences.

Both Pakes (2001) and Diewert (2001) explore the similarities and differences between the hedonic approach and the matched model approach, and both papers note that the matched model suffers a number of biases (selection and new goods) when the rate of technological innovation is high. However, given data of sufficient frequency (quarterly or monthly), the matched model approach will produce an index that fairly closely approximates an hedonic index (see Aizcorbe, Corrado, and Doms (2000) for discussion and equivalent econometric versions of a matched-model index). Using scanner data, however, Silver and Heravi (2002) find significant degradation of coverage of current transactions in the sample used for matched model index construction, even when monthly data are used. Furthermore, exiting models tended to have different rates of price change than continuing models (as measured through the hedonic residual), indicating that even high-frequency matched model approaches may suffer considerably from selection bias.

In addition to bias, the variance of estimated indexes is important. While hedonic indices do not suffer the selection bias that the matched model does, both hedonic and matched model techniques have variance in their estimated price indexes due to sampling. Furthermore, the hedonic indices introduce another source of variance, estimation variance, resulting from the need to estimate the hedonic function. However, preliminary empirical evidence suggests that sampling variance accounts for the majority of variance in the hedonic estimates (Pakes, 2001).

In the context of hedonic price indexes, the term "new goods" has been used to refer to two types of innovation. The first refers to new models of goods that are introduced having different values of characteristics than existing goods in the marketplace. For example, Dell may introduce a new model of PC that has more RAM or a larger hard drive than previous models. The second meaning refers to the introduction of new characteristics. The PC market has seen the introduction of innovations such as the hard drive, portable models (i.e., laptops), CD-ROM, DVD drives, and so on. As Diewert (2001) and Pakes (2001) point out, neither hedonic nor matched model methods account for the welfare gains from the introduction of new goods or characteristics that arise for those consumers whose valuation of a new good exceeds its price. However, Diewert (2001) suggests functional forms that are capable of handling the introduction of new characteristics. In principle, these “flexible” (e.g., quadratic or semi-log quadratic) hedonic functions also allow for the estimation of reservation prices for new characteristics, and thus estimation of the welfare gains resulting from the availability of new characteristics.

IV. Hedonic Price Analysis of Mobile Computers

Few economic studies have focused explicitly on mobile computing devices. A number of papers have examined laptop computer pricing, but have not focused on portability *per se;*. see Nelson, Tanguay, and Patterson (1994); Berndt, Griliches, and Rappaport (1995); Baker (1997), Berndt and Rappaport (2001), Chwelos (1999), and Chwelos (2003). To the extent that these studies have examined portability as a characteristic, it typically has been operationalized in terms of weight or volume, and confined to laptop and notebook computers rather than the full range of mobile computing devices. A number of puzzling – and interesting – results have emerged from this work: parameter estimates are unstable over time; the estimated rate of decline of quality-adjusted prices was lower for mobile computers than for desktops until the late 1990s; and coefficients on characteristics were not equal across mobiles and desktops. For purposes of comparison, we begin to address these questions through the construction of a price index for a relatively unstudied class of (very) mobile computing devices: PDAs. Future work will compare the results for PDAs to those for other mobile and fixed computing platforms.

At least since Griliches (1971), and as reemphasized by Pakes (2001), it has been recognized that hedonic regressions are only a “reduced form” representation of both consumer and producer optimizing behavior. Hence coefficients cannot easily be interpreted in terms of marginal valuation or marginal cost. Nonetheless, users of this methodology in government statistical agencies and elsewhere appear to find parameter instability troublesome. If it reflects only familiar “mechanical” specification problems such as multicollinearity, measurement error, etc., then parameter instability may be dealt with relatively easily with the standard prescription of “more and better data.” On the other hand instability may also be generated by economically significant factors such as failing to control for producer behavior, which presents a much more serious methodological challenge. Absent a fully specified structural model of producer behavior, some progress may be made in stabilizing parameter estimates by instrumenting with variables that capture supply factors, such as semiconductor costs or market concentration measures, or by otherwise accounting for observable aspects of supplier behavior.[3]

In the PC market, one salient aspect of market dynamics is changing markups over the lifecycle of generations of processor technology: much higher margins are obtained on products incorporating a new generation of processor during their first few quarters. It is therefore likely that more stable parameter estimates (and thus more readily comparable price changes) could be obtained with a regression specification that recognizes the product lifecycle explicitly. Chwelos, for example, found relatively stable coefficients within periods of time corresponding to distinctive technology regimes (e.g. 32-bit processor, megabit DRAMs, monochrome LCD screens).

One way to address this problem within the standard hedonic framework is to use regression specifications (indicator variables for "generations", interacted with characteristics such as CPU speed) to estimate "piece-wise" stable coefficients (Pakes 2001). We note, though, that this problem with unstable coefficients has thus far only been observed in models computed at annual frequency. By re-estimating these models using quarterly (or even monthly) data one would be able to evaluate "lifecycle" timing and pricing dynamics much more precisely.

Mobile computers present a challenge for traditional hedonic analysis since, in contrast to desktop computers their design is much less modular and much more integrated. Informed observers have frequently pointed out that the "output" of a computer is not necessarily additively separable on its component-level "inputs" – doubling RAM or processor clock speed will not necessarily result in a doubling of performance (or halving of execution time) in completing tasks; see, e.g., Cole et al. (1986) and Dulberger (1989), and most recently Nordhaus (2001). Differences in performance, therefore, may not be adequately captured by differences in the list of components. Chwelos examined this issue using system "output" benchmark data as a performance characteristic, as well as conventional "input" measures, such as clock

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[3] We note that though the number of distinct computer models sold remains high, the market has become increasingly concentrated in terms of manufacturers. Product variety may also change in important ways over the lifecycle of a technology generation.

speed, memory size etc.; he reports that (at least for desktop PCs) the more easily observable input measures could, in combination, be used as adequate proxies.

In part this finding may reflect the scaling properties of the PC-compatible architecture, but it may also reflect the nature of the product market. With intense product market competition, many PC-compatible computers appear to be priced as the sum of component costs, assembly costs, and a very small operating margin. With homogenous technology and internal design, and highly competitive pricing, "true" performance differences may not be reflected in pricing. By contrast, mobile computers are more heterogeneous in design, contain more proprietary engineering, and rely less on standardized modular subsystems. Thus component lists may be a significantly poorer proxy for performance, and since mobile computers have historically been sold under less intense pricing pressure and with higher margins, some of these performance differences may be visible in pricing. Suggestive evidence in support of this can be seen in the large and highly significant brand effects estimated in prior work involving mobile PCs.

In addition to this performance measurement issue, users' valuations of the characteristics of mobile computers may differ from that of desktops in other important ways. Portability requirements mean that designers of mobile computers have to make quite different trade-offs, which may be difficult to capture fully using simple proxy variables. "Portability" is itself challenging to measure consistently over time. Prior studies have used "footprint", weight, volume, density, and other characteristics, but it is not clear how well these capture portability. Further refinement and testing of these measures are necessary. Furthermore, in minimizing size and weight, engineers have had to solve a variety of challenges ranging from heat dispersion and power management to resistance to mechanical and environmental shocks, miniaturization of components, etc.[4] Compared to desktops, mobile computers may therefore have much more unobserved variation in desired performance characteristics, above and beyond computation power and storage capacity. These may include power consumption, battery efficiency, reliability, ergonomic aspects of "usability", and durability. Aesthetic aspects of product

[4] Critical design and technology choices advances for mobile computers include: power source (internal vs. external, weight and size, capacity, battery technology, e.g., alkaline, nickel cadmium, nickel metal hydride, lithium ion, lithium polymer); processor (performance, word size, power consumption, variable speed); heat dispersion (radiant, fan); input technology (stylus versus keyboard); and display type (size, resolution, color, active/passive matrix, power consumption).

design also appear to be important to users.   Again, some of this variation can be captured by brand indicators, but there is no reason to assume that these would be stable over time. Modeling this unobserved component of quality is a challenge, all the more so when we consider PDAs and other handheld devices that may be built as closed systems with proprietary technology, and are typically sold bundled with a range of software applications in ROM.

We are aware of only one previous study, an undergraduate honors paper at Northwestern University, that has constructed a price index for PDAs (Vonnahme (2002)). Using the set of characteristics published in the buyer's guides of "PocketPC Magazine" and "Pen Computing Magazine," PDAs were found to have declined in quality-adjusted prices at an average rate of 14-18% per year over the period 1999 through the first quarter of 2002. However, the valuation of performance and mobility in PDAs remains poorly understood. Indeed, the feature set of a PDA is evolving rapidly, and definitions of what a PDA is and is not, especially versus related devices such as smart phones and pagers, are unclear. Moreover, the very concept of "performance" in a PDA has yet to be clearly defined.

However, several essential characteristics of PDAs have emerged: they are small, portable, battery powered, and accomplish data input through a stylus and handwriting recognition and/or a drastically miniaturized keyboard typically operated with one or two thumbs, and include a calendar and personal information manager (contact information) as core applications. PDAs are usefully distinguished from very small notebook computers (mini-notebooks) that possess a QWERTY keyboard, typically ¾ sized, that permits standard ten-finger typing. As discussed above, current models of PDAs may also incorporate a number of other types of hardware functionality, such as a digital camera, a cellular telephone, data or internet connectivity via cellular, wireless, and Bluetooth networking, MP3 player capability, and biometric security via a fingerprint reader. PDAs that include cellular telephone capability (or cellular telephones that include PDA capabilities) are referred to as "smart phones".

V. Data

The worldwide market for PDAs was estimated at 11.45 million units ($3.70 billion) in 2003, with 70% of units being purchased by individuals and 30% by enterprises (Gartner 2004). For the current study, data on the characteristics and prices of PDAs and smart phones for the years 1999-2004 were obtained from Gartner, Inc.[5] Gartner collects data annually from PDA manufacturers, although the timing varies from year to year.[6] Prices are supplied by manufacturers, and should thus be interpreted as list rather than transaction prices. Use of internet shopbots reveals that, although there exists considerable variability in transaction prices, there is no trend in the median price on the internet versus MSRP over time; thus, our price indexes based on list prices should not be biased.[7]

The Gartner data contained a number of missing characteristics, which were "backfilled" using a variety of sources (product fact sheets, product reviews, vendor listings, buyers' guides, etc.). Excluding observations for which a price in US dollars was not specified yielded us a total of 239 observations for which data on the complete set of characteristics was obtained. The distribution of observations across years and brands is presented in Table 1. Average values of key characteristics are presented in Table 2.

Nominal prices for both PDAs and smart phones are dropping across the timeframe, and, as expected, there are significant trends in terms of the performance and form factor of both types of machines. Over the six years, we observe that PDAs have become smaller, lighter, and provide more colors on albeit smaller screens. Smart phones have likewise become smaller and lighter, as well as dramatically more colorful. Increasing performance in both platforms is embodied primarily through the introduction of new generations of central processing units (CPU's) that are relatively more energy efficient and operate at higher clock speeds (measured in MHz); likewise, the quantity of all types of memory (RAM, ROM, and Flash ROM) increases significantly over time. However, although performance has increased in both platforms, there remains a distinct difference between PDAs and smart phones, with the former tending to have more

[5] All of the machines in the "mini-notebook" category were eliminated from the sample; due to their different cost trade-offs and user benefits than PDAs, this class of machine is more appropriately studied in the class of portable PCs (i.e., notebook or laptop).
[6] The period of observations is not exactly 12 months, and varies slightly from year to year. The actual period between adjacent observations is 12, 10, 11, 14, and 7 months respectively.
[7] See, for example, www.nextag.com for pricing histories of PDAs over time.

powerful processors, larger memories, and much longer battery lives.[8] (A full description of the variables used in this study is given in Table 4.)

As can be seen from Table 3, some characteristics have converged over time, whereas others have diverged. Notably, the screen size, weight, volume, battery life, and number of colors of PDAs have converged to a *de facto* standard of a unit with a 3.5-inch screen supporting 65,536 colors (2^{16}) that weighs about 5.5 ounces in a volume of about 8 cubic inches and has a rated battery life of 8 hours. However, other characteristics have diverged over time, with, for example, the variance in MHz, RAM, Flash, digital cameras, and WiFi networking increasing over time. It appears that the characteristics relating to human factors and portability have achieved a "sweet spot," i.e., PDAs have achieved a size and weight that fits well in an average human adult palm (as well as a pocket) and is light enough to be carried easily. Other converging characteristics, such as screen size, battery life, and number of colors appear to be at their maximum possible value given the current state of display and battery technologies, subject to the constraints of size, weight, and volume. In terms of capabilities – processing power, battery life, colors, communications capabilities, operating systems, digital cameras, biometrics, etc. – PDAs continue to exhibit enormous and perhaps increasing product variety.[9] The range of characteristics and prices available in the marketplace is strikingly large, much larger than, for example, desktop PCs. Order-of-magnitude differences in the prices and performance can be found between "value" (e.g., Palm Zire) and cutting edge PDAs (e.g., HP iPAQ h5550) sold in the same year.

VI. Preliminary Analysis: Regression Results

The base case specification for estimation of the hedonic function is a log-log model using the explanatory variables outlined in Table 4. Exact singularity prevents all

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[8] The shorter battery life for smart phones reflects the power drain associated with using their cellular telephone capabilities.

[9] Interestingly, there are some types of product variety that are clearly welfare-enhancing, such as the availability of models with and without digital cameras or WiFi networking. This type of product variety allows consumers to choose the PDA with the feature set they find most desirable. However, there are other types of product variety that are probably welfare-reducing, because they create confusion or incompatibility. For example, the proliferation of types or standards for expansion slots (e.g., compact flash types 1 and 2, secure digital, multi-media cards, smart media, etc.) creates difficulty in sharing information between PDAs or between a PDA and a desktop, and can create a measure of lock-in to a particular brand or platform.

of the indicator variables from being included, so several are dropped, making the "default" or reference case PDA one that has an "MIPS 1" processor and a "Palm OS". Likewise, perfect collinearity between weight, volume, and density in the log-log specification requires that one of the three be eliminated, and thus weight was dropped. Finally, the total number of expansion slots is defined as the sum of the types of slots included. A decision was made to employ the summary measure in place of identifying each type of slot since there is little expected user value or producer cost difference among the different types of slots.[10] In addition to the characteristics outlined in Table 4, indicator variables for the years 2000, 2001, 2002, 2003, and 2004 were included in the regression; 1999 is the omitted year.

In the base case regression, lnMHz and various processor indicator variables are included, but there are no interactions involving clockspeed and processor type. Regression results are given in Table 5. Recall from Table 1 that the number of PDA observations per year is roughly constant at 34, but that the number of smart phone observations grows from one in 1999 and 2001 to 17 in 2004.

Examination of the residuals indicates that there may be vendor effects. Column 2 introduces vendor indicators, although only a few are significant (the eliminated vendor is Hewlett-Packard). However, a test of the joint restriction of no vendor effects is soundly rejected ($F_{18, 162} = 5.95$, $p < =.0001$).

Given the differences in average characteristics across PDAs and smart phones (see Table 2), we test for differences between phones and PDAs. First, note that the dphone indicator variable is highly significant, indicating that smart phones are priced above PDAs for the same level of performance. Given the additional functionality associated with cellular capability, this finding may not be surprising; however, smart phones are typically sold at a price that includes a 1-2 year service contract. This contract represents a stream of liabilities associated with the phone, and these monthly payments may be used to subsidize the purchase price of the smart phones. Thus, the price effect of the dphone indicator is not clear *a priori*. To test for equality of parameter values across the two platforms, we construct interaction terms between the dphone and

[10] In addition, certain types of expansion slots, such as Sony's "memory stick" are proprietary to individual vendors, introducing further collinearity issues when vendor dummy variables are included in the regression.

key performance characteristics: MHz, RAM, ROM, Flash, Pixels, Screen, Colors, BatLife, Weight, and Volume. Parameter equality is strongly rejected ($F_{10, 162} = 9.10$, $p < =.0001$).[11] We thus split the sample into PDAs and smart phones; however, given the limited data for smart phones (thirty-six observations across five years), hedonic analysis is not feasible. Therefore, we restrict our analysis to the 206 observations for PDAs. Column 3 presents the results of the regression including vendor indicators for the sample of PDAs only. [12]

The regression fit improves significantly, with an adjusted $R^2 = 0.8400$. The introduction of the vendor indicators and the restriction to only PDAs creates perfect collinearity with the operating system indicators, as vendors only make PDAs for one type of operating system; therefore, the dOtherOS indicator variable is also dropped. Vendor indicators remain significant ($F_{11, 138} = 5.52$, $p < =.0001$). The year indicator variables are negative, statistically significant, and increasing in absolute magnitude in later years, indicating a negative price trend. Major drivers of price include battery type, especially the later-generation technologies lithium polymer and lithium ion, although battery life itself is insignificant after controlling for battery type. For communication ports, all were insignificant except for USB and the Bluetooth and WiFi wireless ports in later models. Neither weight nor volume is statistically significant, indicating that either portability is not individually valued or that features and portability are inversely correlated.

With regard to performance, the indicator variables for the different types of processors are largely significant, indicating that these processors provide significantly more value than the default "MIPS 1" processors present in the early Palm Pilot models. Likewise, the coefficient on MHz is positive and statistically significant. Given the limited variation of MHz within processor types, there may simply not be enough variation to disentangle the impacts of clockspeed from processor generation. The

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[11] For space reasons, the individual coefficients are not presented in Table 5. Only the interactions between dphone and weight, volume, and battery life are individually significant.

[12] We tested for homoskedasticity using both the White and Cook-Weisberg tests. The full White test fails to reject homoskedasticity ($\chi^2_{196} = 201.69$, p = 0.3752), whereas the Cook-Weisberg test does reject homoskedasticity ($\chi^2_1 = 6.42$, p = 0.0113). Examination of the squared residuals did not indicate a strong relationship with any of the characteristics or their products or squares, including time dummies. However, given the Cook-Weisberg results, we adopt heteroskedasticity robust standard errors.

coefficients on the quantity of all three types of memory are positive and significant, although ROM is only weakly so.

As a check on sensitivity to specifications, we tested an alternate specification in which lnMHz is interacted with each of the processor types, instead of a separate lnMHz and processor indicator variable. The two approaches were nearly identical in terms of model fit, and coefficient estimates for other variables were little affected. Given the lack of difference across the approaches, we opt for the conceptually simpler lnMHz plus processor indicator variable approach.

The characteristics chosen for the hedonic regression reflect, in our judgment, the essential sources of user value and producer cost in the PDA platform, as advised by Triplett (1989). However, not all of the characteristics are statistically significant. Column 4 of Table 5 presents a specification of the hedonic function with insignificant regressors deleted using the stepwise approach. The results in columns 3 and 4 are very similar, with a few additional characteristics becoming statistically significant: lnColors, lnVolume, dProc_ARMv7, dcradle, and the Casio and IBM vendor indicators. Only one previously significant characteristic is removed, the indicator for nickel-metal hydride batteries.[13] An F-test fails to reject the hypothesis that the year indicators are constant across columns 3 and 4 ($F_{4, 138} = 0.23$, $p <= 0.9598$). Given the similarity across columns 3 and 4, it makes little difference which specification is used as the basis for constructing price indexes, so we opt for the more inclusive specification in column 3 as we explore parameter stability across years.

To test for parameter stability over time, we take three approaches. First, we begin by estimating pairs of adjacent years and test whether additional years pool with the pairs of years (i.e., that coefficients are stable across these years). Results indicate that parameters are stable across 1999-2003; corresponding parameter estimates are presented in column 1 of Table 6. The 2003-2004 pair of years is estimated separately from 1999-2003 in column 2. Given the small number of observations in these subperiods, as well as the number of parameters being estimated, we are not confident in

[13] Nickel Metal Hydride batteries appeared in rechargeable devices (e.g., cell phones, laptops, PDAs) briefly as an improvement over NiCad batteries, but were quickly replaced by Lithium-based batteries.

the stability of these regressions, especially the 2003-2004 subsample, in which multicollinearity is also an issue (average VIF = 85.44).

Thus, we look for other approaches to exploring parameter stability over time that allow for pooled estimation. The second approach constructs a "time" index that begins at zero and increases by 1 in each year. This time index is interacted with the key characteristics displaying time trends (i.e., MHz, RAM, ROM, Flash, Pixels, Screen, Colors, BatLife, Weight, and Volume). Three interactions are significant, indicating that the elasticity of market price with respect to RAM, Flash ROM, and Screen size is changing over time. Of course, this approach implicitly assumes that the change in parameter values over time can be captured with a simple linear trend; given that we have no reason to assume this to be the case, we explore a third, more flexible alternative.

Our final approach to parameter stability over time is to construct interaction terms between the aforementioned key characteristics and the indicator variables for the years 2000 – 2004. This approach thus allows for a different elasticity valuation of each characteristic in each year. Multicollinearity issues reduce the power of the tests performed when all of these time indicator interaction terms are introduced simultaneously, so we will follow a two-step procedure. First, we will introduce and test the time indicators for each characteristic individually. Second, we will then test the significance of the time indicators for each characteristic identified as significant in the first stage when all of the time indicator interactions are estimated simultaneously.

When estimated individually in step one, the time indicator interactions with the characteristics produce jointly significant sets of interaction terms for the characteristics Flash ROM, ROM, Screen, BatLife, Weight, and Volume. When tested jointly in stage 2, Screen, BatLife, Weight, and Volume remain significant. The regression including these four sets of time indicators is presented in column 4 of Table 6. Multicollinearity is present in all of columns 2-4, as the average VIF exceeds 30 for each of these specifications. While this will not bias our estimated price indexes, it does of course increase the variance of the resulting indexes. We now turn to calculating price indexes for PDAs.

VII. Hedonic Price Indexes for PDAs

Because we do not have comprehensive model-specific quantity or sales data, we use unweighted price ratios in calculating price indexes. For purposes of comparison we first construct a matched model price index, which is based on 68 of our 203 observations (30.5%). As is seen in the first column of Table 7, the matched model price index declines from 1.000 in 1999 to 0.3548 in 2004, an annual average growth rate (AAGR) of –18.75%.[14] By comparison, the hedonic price index using the indicator variable method based on the pooled parameter estimates in Table 5 declines at a more rapid rate, with an AAGR of –25.81%, while that based on the Table 6 time indicator specification parameter estimates declines at a very similar rate of –25.95%. The approximately 7% difference in AAGRs between the matched model and each of the hedonic indexes likely reflects the selection bias in surviving models, i.e., that the matched model index truncates the distribution of price changes and produces an upward-biased index (Pakes 2001). The positive and significant coefficient on the Age parameter across all specifications in Table 5 indicates that surviving models are priced above the average for the sample based on their objective characteristics. The matched model and hedonic indexes diverge most widely across 2000-2002; during this period, surviving models were unrepresentative of the average model in that they had: slower and less powerful processors; smaller, less colorful, and lower-resolution screens; and less RAM and ROM memory. In descriptive terms, the surviving models of this era were either the relatively basic organizer-style PDA (e.g., Palm m100, Sharp Zaurus) or the wireless email-enabled devices (e.g., RIM Blackberry 850), both of which fell behind the cutting edge in terms of power, colors, performance, and battery technology.

Columns 4 and 5 of Table 7 present hedonic price indexes based on the characteristics prices approach, whereas columns 6 and 7 use the "imputation" or "hybrid" approach. The characteristics prices approach uses the actual prices in the base period, and the hedonic estimates of prices in the reference period. The hybrid method uses the actual prices where possible to calculate price relatives (i.e., the matched model formula), and uses the hedonic function to estimate prices of unmatched models. For our

[14] Of the 34 model observations in 1999, 17 survived as matched models into 2002; 14 of 34 survived from 2000 to 2001; 11 of 38 survived from 2001 to 2002; 6 of 34 survived from 2002 to 2003; 14 of 30 survived from 2003 to 2004.

estimates, we construct both characteristics prices and hybrid indexes using both the pooled results from Table 5 and the time indicator results from Table 6. The characteristics prices and hybrid indexes span the range of –21 to –25% AAGR, and all four fall between the matched model and the indicator variable estimates. We have a preference for the hybrid relative to the other methods because it makes use of matched models where available; we also prefer the time indicator specification because it does not restrict the hedonic coefficients to be constant over time. Thus, our preferred price index is the "Complete Hybrid Time Indicators", presented in column 7, and which has with an AAGR of approximately –21% over the six years in our sample.

VIII. Conclusion

In this paper we have examined the relation between prices, performance, and features of an "ultraportable" computer technology -- the personal digital assistant. The PDA platform was found to have undergone significant innovation in the period 1999-2004, with substantial performance improvements accompanied by declining average nominal price for the models in our dataset. Quality-adjusted prices derived by hedonic regression fell at an average annual rate of approximately 21% per year over this period. A matched model index fell at a slightly lower, though still substantial rate.

These rates of decline in quality-adjusted prices suggest large welfare gains for PDA purchasers. Nonetheless, at 20-25% per year, the rate of price decreases is significantly lower than that seen in desktop and laptop computers, which by some estimates was 30-40% per year during this period. Like other reduced form hedonic analyses, our method cannot disentangle changes in component costs and producer markups from changes in consumers' marginal willingness to pay. But several features of the PDA market suggest to us possible explanations for slower rates of decline in their quality-adjusted prices relative to PCs.

Compared to other personal computing devices, PDA technology is less modular and contains more proprietary components, produced in smaller volumes. Manufacturing and component costs may therefore have been declining at slower rates than for PCs. Compared with the "beige box" world of PCs, PDA product designs are more fluid, and tend to emphasize more non-functional design features which are difficult to capture using hedonic methods. And unlike the PC marketplace, a single dominant software/hardware standard has not yet emerged, which may allow higher markups on more differentiated products, and generate quite different producer behavior. Interestingly, controlling for other characteristics, PDA quality-adjusted prices were significantly lower for PDAs running the Windows CE operating system, suggesting a relationship between network externalities and pricing.

PDAs stand at one extreme of a spectrum of "portability" of computing devices. At the other extreme, desktop PCs are essentially fixed at a specific location. In the middle lie laptop computers, which have become much smaller and lighter over time since the first "luggable" models of the early 1980s, as well as "tablet PCs," "sub-notebooks," and other devices.[15] As an ultra-portable technology, better understanding of the pricing of computer functionality embedded in PDAs is thus a first step towards greater insight into the economics of portability.

Immediate items on our research agenda include updating the frequency of price/characteristics observations to a quarterly basis, thereby constructing a price index with more frequent periodicity to better illuminate product lifecycle issues. Work is also ongoing to produce updated and comparable price indexes for desktop personal computers as well as laptops, and to compare these three categories of computing hardware. Ultimately, inter-category demand effects will be examined with the objective of producing an "elasticity of portability" and an understanding of whether these classes of computing hardware are substitutes or complements.

[15] Arguably the first portable computer was the IBM 5100, introduced in 1975, or the Osborne in 1981, but the Compaq was the first PC-compatible "portable" – actually a "luggable" at 28 pounds!

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Table 1: Observations by Year, Brand, and Platform

PDAs

Vendor	1999	2000	2001	2002	2003	2004	Total
Casio	3	3	4	4	2	3	19
Compaq	4	3	5	7			19
Dell					2	4	6
Handspring	2	2	5	4			13
Hewlett-Packard	4	5	5	1	5	6	26
IBM	2	1	2				5
Palm (3Com in 1999)	6	10	7	6	8	8	45
Psion	4	1	2				7
Research In Motion	1	2	4	4	2	2	15
Sharp	8	7					15
Sony			4	5	8	4	21
Toshiba				3	3	6	12
Total	34	34	38	34	30	33	203

Smart Phones

Vendor	1999	2000	2001	2002	2003	2004	Total
Handspring				3			3
Kyocera			1	1	1	1	4
Motorola				1			1
Nokia					1		1
Palm					1	2	3
Qualcomm	1						1
Research In Motion					5	7	12
Samsung				1	2	4	7
Siemens					1	1	2
Sony Ericsson						2	2
Total	1	0	1	6	11	17	36

Table 2: Mean Characteristics by Year and Platform

PDAs							
Characteristic	1999	2000	2001	2002	2003	2004	Total
Nominal Price	$483.03	$439.53	$387.95	$400.29	$375.23	$362.42	$408.55
MHz	52.53	54.12	66.95	118.00	192.77	262.82	121.37
RAM (MB)	10.24	10.16	12.81	25.27	36.83	50.76	23.74
ROM (MB)	5.85	4.76	5.68	7.03	10.93	11.33	7.48
Flash ROM (MB)	0.147	0.50	1.92	12.29	8.97	13.73	6.08
Pixels (display resolution)	83840.59	64528.24	52245.79	53987.06	84837.50	80938.79	69367.22
Display size (diag. inches)	4.78	4.29	3.600	3.37	3.34	3.29	3.79
Colors	11612.06	10023.00	15226.32	37589.29	56799.07	56600.36	30364.59
Weight (ounces)	10.75	8.84	6.14	5.69	5.95	5.68	7.19
Volume (cubic inches)	19.88	14.91	9.20	9.36	9.09	8.36	11.82
Battery life (hours)	66.97	109.68	110.97	61.28	29.47	25.47	69.12

Smart Phones							
Characteristic	1999	2000	2001	2002	2003	2004	Total
Nominal Price	$650.00		$499.00	$557.67	$464.45	$398.11	$454.77
MHz	16.00		16.00	30.17	74.09	72.53	62.80
RAM (MB)	2.00		8.00	11.33	15.00	11.59	12.22
ROM (MB)	0.00		0.00	0.33	8.73	0.00	2.72
Flash ROM (MB)	0.00		0.00	3.17	13.27	10.47	9.53
Pixels (display resolution)	38400.00		38400.00	26880.00	57282.91	42279.53	44401.78
Display size (diag. inches)	3.69		3.50	2.92	3.44	3.28	3.28
Colors	2.00		2.00	769.00	36120.00	31593.88	26084.28
Weight (ounces)	10.00		7.34	5.77	5.99	5.45	5.85
Volume (cubic inches)	22.57		12.04	9.82	11.37	9.88	10.74
Battery life (hours)	6.00		5.00	2.88	4.44	4.73	4.38

Table 3: Convergence of PDA Characteristics, Standard Deviation of Characteristics within Years

Characteristic	1999	2000	2001	2002	2003	2004	1999-2004
Nominal Price	210.03	189.70	115.94	170.71	183.26	149.45	174.26
MHz	42.17	53.65	64.41	125.77	132.60	142.51	126.45
RAM (MB)	8.79	9.95	12.80	24.74	29.53	33.43	26.27
ROM (MB)	6.75	7.03	6.97	12.73	19.14	21.54	13.55
Flash ROM (MB)	0.50	1.28	3.06	14.60	12.67	14.75	11.23
Pixels (display resolution)	62595.59	47877.74	33377.97	30302.92	41362.06	30100.03	44151.82
Display size (diag. inches)	1.35	1.08	0.58	0.39	0.45	0.44	0.97
Colors	25337.50	23426.03	26866.88	32397.93	22655.69	22089.30	32344.49
Weight (ounces)	8.38	4.40	1.87	1.08	1.31	1.10	4.44
Volume (cubic inches)	16.89	9.31	2.75	1.82	2.36	1.54	9.04
Battery life (hours)	91.73	152.59	173.93	116.27	89.31	85.45	128.03

Table 4: Variable Descriptions

Variable	Description
dProc_ARMv5	0-1 Indicator for processor based on the ARM v5 architecture standard
dProc_ARMv7	0-1 Indicator for processor based on the ARM v7 architecture standard
dProc_ARMv9	0-1 Indicator for processor based on the ARM v9 architecture standard
dProc_ARMv11	0-1 Indicator for processor based on the ARM v11 architecture standard
dProc_M68x	0-1 Indicator for processor based on the Motorola 68x architecture (e.g., DragonBall family)
dProc_MIPS1	0-1 Indicator for processor based on the MIPS architecture (e.g., NEC VR 4111, 4121, etc.)
dProc_MIPS2	0-1 Indicator for processor based on the MIPS architecture (e.g., NEC VR 4122)
dProc_O16	0-1 Indicator for other 16-bit processor
dProc_O32	0-1 Indicator for other 32-bit processor
dpalmOS	0-1 Indicator for Palm operating system
dotherOS	0-1 Indicator for other operating system
dwinOS	0-1 Indicator for Windows (CE, Pocket PC) operating system
dIR	0-1 Indicator for infrared port
dserial	0-1 Indicator for serial port
dUSB	0-1 Indicator for USB port
drj11	0-1 Indicator for rj11 (telephone) port
dblue	0-1 Indicator for Bluetooth wireless support
dWiFi	0-1 Indicator for WiFi (802.11b) wireless support
dmemstik	0-1 Indicator for Sony Memory Stick expansion slot
dsdmmc	0-1 Indicator for Secure Digital or Multimedia Memory Card expansion slot
dcf	0-1 Indicator for Compact Flash expansion slot
dsmartc	0-1 Indicator for Smart Media expansion slot
Slots	The total number of expansion slots
dbiometrics	0-1 Indicator for biometric (fingerprint reader) capability
dcamera	0-1 Indicator for digital camera
dcradle	0-1 Indicator for an included docking cradle
dfront	0-1 Indicator for a “frontier” model
dMP3	0-1 Indicator for MP3 player
dpagerdata	0-1 Indicator for cellular email/data capability
dphone	0-1 Indicator for cellular telephone capability
dservice	0-1 Indicator for price including a contract for wireless service
dalk	0-1 Indicator for disposable alkaline batteries
Bat	Claimed battery life in hours
dlipoly	0-1 Indicator for rechargeable lithium polymer battery
dnimh	0-1 Indicator for rechargeable nickel metal hydride battery
dbliion	0-1 Indicator for rechargeable lithium ion battery
MHz	Clock speed of the CPU, measured in millions of cycles per second
RAM	Quantity of random access memory measured in megabytes (MB)
ROM	Quantity of read-only memory measured in MB
Flash	Quantity of Flash memory (erasable programmable ROM) measured in MB
Colors	Number of colors/greyscales supported by the display
Pix	Number of pixels in the display
Screen	Screen size, measured diagonally, in inches
dVendorX	0-1 Indicator variable for vendor X, nineteen different vendors in total (see Table 1)
Volume	Volume of the PDA in cubic inches
Weight	Weight of the PDA in ounces

Table 5: Hedonic Regression Results
Huber-White robust standard errors are in parentheses

	Phones & PDAs Base	Phones & PDAs Vendors	PDAs Vendors	PDAs Significant
lnMHz	0.2830*** (0.0651)	0.2308*** (0.0704)	0.1645** (0.0696)	0.1335** (0.0557)
lnRAM	0.1076** (0.0482)	0.1419*** (0.0495)	0.1790*** (0.0400)	0.1891*** (0.0375)
lnROM	0.0341 (0.0248)	0.0378 (0.0351)	0.0666* (0.0344)	0.0674*** (0.0213)
lnFlash	0.0619** (0.0276)	0.0528 (0.0334)	0.0738** (0.0331)	0.0837*** (0.0239)
lnPixels	0.0306 (0.0649)	0.1220 (0.0820)	0.1623* (0.0830)	0.1638** (0.0762)
lnScreen	0.1986 (0.2175)	0.2014 (0.2493)	0.2833 (0.2505)	
lnColors	0.0165* (0.0090)	0.0127 (0.0108)	0.0120 (0.0077)	0.0123* (0.0067)
lnBatLife	-0.0447 (0.0296)	-0.0083 (0.0338)	0.0079 (0.0265)	
lnWeight	0.3120** (0.1385)	0.1285 (0.1418)	0.0331 (0.1185)	
lnVolume	-0.0156 (0.1180)	0.0434 (0.1172)	0.1021 (0.1035)	0.1477** (0.0656)
dProc_ARMv5	0.4636*** (0.1462)	0.5819*** (0.1973)	0.6716*** (0.1828)	0.7328*** (0.1410)
dProc_ARMv7	0.2672* (0.1592)	0.2447 (0.1965)	0.1837 (0.1706)	0.2600* (0.1380)
dProc_ARMv9	0.3240*** (0.1129)	0.4302*** (0.1470)	0.5448*** (0.1496)	0.5552*** (0.1186)
dProc_ARMv11	0.2145* (0.1269)	0.3790** (0.1734)	0.4904*** (0.1661)	0.5229*** (0.1349)
dProc_M68x	0.6727*** (0.1539)	0.7793*** (0.2184)	0.8573*** (0.2402)	0.8427*** (0.1689)
dProc_MIPS2	0.0257 (0.0872)	-0.0457 (0.1048)	0.0597 (0.1006)	
dProc_O16	0.2592*** (0.0807)	0.4065** (0.1590)	0.3741*** (0.1388)	0.3642*** (0.0809)
dProc_O32	0.8975*** (0.1619)	0.9830*** (0.1763)	0.8012*** (0.1586)	0.8384*** (0.1169)
dfront	0.2137*** (0.0451)	0.2116*** (0.0517)	0.0987** (0.0386)	0.1006*** (0.0373)
dotheros	0.4126*** (0.1326)	0.3283 (0.2681)		
dwinos	-0.2793** (0.1087)	-0.5128** (0.2081)	-0.9506*** (0.1873)	-0.9243*** (0.1645)
dir	0.1132 (0.1148)	0.1834 (0.1671)	-0.0387 (0.1501)	
dserial	0.0766 (0.0482)	0.1447** (0.0552)	0.0890* (0.0524)	0.1070** (0.0412)
drj11	-0.2685* (0.1494)	-0.1642 (0.1605)	-0.1160 (0.1366)	
dusb	-0.0111 (0.0612)	-0.0003 (0.0764)	0.0922* (0.0514)	0.1127** (0.0482)
dblue	0.1202* (0.0641)	0.1145* (0.0682)	0.1169* (0.0611)	0.1259** (0.0550)
dwifi	0.1695** (0.0719)	0.1498* (0.0770)	0.1647** (0.0667)	0.1775*** (0.0604)
lnSlots	0.0848 (0.0957)	0.1878* (0.1069)	0.2962*** (0.1109)	0.2731*** (0.0932)
dcradle	0.0024 (0.0428)	0.0294 (0.0536)	0.0779 (0.0530)	0.0931** (0.0394)
dbiometrics	0.1387 (0.1176)	0.1528 (0.1258)	0.2071* (0.1146)	0.2194** (0.1020)
dcamera	0.1068 (0.0767)	0.2732** (0.1127)	0.2682** (0.1070)	0.3327*** (0.0866)
dpagerdata	0.2634* (0.1586)	0.1702 (0.1614)	-0.1113 (0.1430)	
dlipoly	0.2697***	0.3840***	0.3509***	0.3138***

	(0.0928)	(0.1215)	(0.1050)	(0.0798)
dnimh	-0.1733	-0.0368	0.1423*	
	(0.1660)	(0.1350)	(0.0799)	
dbliion	0.2247**	0.2920***	0.3139***	0.3143***
	(0.0893)	(0.1018)	(0.0887)	(0.0567)
dservicefees	0.0553	0.2368**	0.5030***	0.4225***
	(0.0988)	(0.0974)	(0.1408)	(0.1085)
d2000	-0.1534***	-0.1318***	-0.1666***	-0.1715***
	(0.0504)	(0.0493)	(0.0455)	(0.0411)
d2001	-0.3668***	-0.3579***	-0.4282***	-0.4576***
	(0.0747)	(0.0798)	(0.0676)	(0.0568)
d2002	-0.7092***	-0.7307***	-0.9067***	-0.9519***
	(0.0974)	(0.1175)	(0.0952)	(0.0731)
d2003	-1.0685***	-1.0823***	-1.2510***	-1.3271***
	(0.1111)	(0.1376)	(0.1119)	(0.1066)
d2004	-1.1676***	-1.1548***	-1.3215***	-1.4051***
	(0.1114)	(0.1386)	(0.1069)	(0.0886)
Age	0.0942***	0.0722**	0.0789***	0.0830***
	(0.0336)	(0.0330)	(0.0283)	(0.0275)
dphone	0.3886***	0.2688*		
	(0.1109)	(0.1611)		
constant	2.9188***	1.9936*	2.1905**	2.5864***
	(0.6856)	(1.0097)	(0.9296)	(0.7524)
Casio		0.2074	0.1840	0.1738**
		(0.1405)	(0.1309)	(0.0804)
Compaq		0.0309	0.0122	
		(0.1346)	(0.1257)	
Dell		-0.0511	-0.1199	
		(0.1529)	(0.1512)	
Handspring		-0.0758	-0.6533**	-0.7286***
		(0.2415)	(0.2540)	(0.1784)
IBM		0.0930	-0.3884	-0.4052**
		(0.2190)	(0.2573)	(0.1758)
Kyocera		0.2678		
		(0.2815)		
Motorola		0.2670		
		(0.2851)		
Nokia		-0.5930**		
		(0.2777)		
Palm		-0.2278	-0.6310***	-0.6679***
		(0.1997)	(0.2340)	(0.1582)
Psion		0.0221	0.0047	
		(0.1907)	(0.1919)	
Qualcomm		0.1005		
		(0.2884)		
RIM		0.0956	0.2913*	0.2485***
		(0.1558)	(0.1507)	(0.0658)
Samsung		-0.1199		
		(0.2146)		
Sharp		-0.0643	-0.0307	
		(0.1928)	(0.1961)	
Siemens		0.3973**		
		(0.1686)		
Sony		-0.4105*	-0.9388***	-0.9150***
		(0.2437)	(0.2877)	(0.2259)
Sony Ericsson		-0.4987		
		(0.3407)		
Toshiba		0.0815	0.0411	
		(0.1308)	(0.1237)	
N	239	239	203	203
Adjusted R^2	0.7403	0.7621	0.8400	0.8470
RMSE	0.2307	0.2208	0.1838	0.1797

Notes: *** significant at the 1 percent level
** significant at the 5 percent level
* significant at the 10 percent level

Table 6: Regressions using Time interactions

	1999-2003	2003-2004	Time Interactions	Time Indicators
lnMHz	0.1902**	0.4403**	0.1753**	0.1177
	(0.0761)	(0.1932)	(0.0690)	(0.0753)
lnRAM	0.1807***	-0.0292	0.2212***	0.1685***
	(0.0428)	(0.1206)	(0.0519)	(0.0350)
lnROM	0.0525	0.1762	0.0962***	0.0429
	(0.0352)	(0.1529)	(0.0317)	(0.0421)
lnFlash	0.0665**	0.1654	-0.0464	0.1370***
	(0.0325)	(0.1682)	(0.0593)	(0.0357)
lnPixels	0.0937	0.6600**	0.2429***	0.3384***
	(0.1305)	(0.2562)	(0.0783)	(0.0763)
lnScreen	0.3781	3.3313**	-0.1536	0.9851***
	(0.2758)	(1.5062)	(0.3310)	(0.3452)
lnColors	0.0153*	-0.0486	0.0160**	0.0158***
	(0.0084)	(0.0421)	(0.0073)	(0.0060)
lnBatLife	0.0132	0.2709**	0.0326	-0.0677
	(0.0309)	(0.1094)	(0.0267)	(0.0420)
lnWeight	0.0213	1.3624**	-0.0601	0.3934**
	(0.1356)	(0.6136)	(0.1248)	(0.1719)
lnVolume	0.0842	-0.2752	0.1608	-0.5840***
	(0.1128)	(0.2292)	(0.1029)	(0.1939)
dProc_ARMv5		-0.4412	0.5818***	0.6187***
		(0.4402)	(0.1964)	(0.1863)
dProc_ARMv7	0.1489		0.0691	0.2896
	(0.1665)		(0.1740)	(0.1777)
dProc_ARMv9	0.4297**	-0.6259*	0.5339***	0.6340***
	(0.1646)	(0.3478)	(0.1484)	(0.1478)
dProc_ARMv11	0.3457*	-0.8167*	0.4377**	0.5778***
	(0.1776)	(0.4538)	(0.1746)	(0.1720)
dProc_M68x	0.4150		0.7967***	0.8490***
	(0.3088)		(0.2630)	(0.2582)
dProc_MIPS2	0.0539	-0.9720*	0.1245	0.3064**
	(0.1094)	(0.5413)	(0.0899)	(0.1212)
dProc_O16	0.3146**		0.3725***	0.6023***
	(0.1271)		(0.1384)	(0.1377)
dProc_O32	0.6709***		0.8083***	0.8517***
	(0.1468)		(0.1596)	(0.1367)
dfront	0.1170**	-0.1157	0.0813**	0.1033***
	(0.0446)	(0.0914)	(0.0388)	(0.0386)
dotheros	-0.0206			
	(0.3014)			
dwinos	-0.8186***	-3.9658***	-1.0438***	-1.0884***
	(0.1819)	(0.6750)	(0.2001)	(0.1897)
dir	-0.1156	0.5161	-0.0541	-0.0518
	(0.1381)	(0.5851)	(0.1293)	(0.0994)
dserial	0.0872	0.0991	0.0411	0.0683
	(0.0672)	(0.1482)	(0.0508)	(0.0502)
drj11	-0.1052		-0.0242	-0.2004
	(0.1333)		(0.1545)	(0.1354)
dusb	0.0635	0.1941**	0.0822*	0.0547
	(0.0556)	(0.0893)	(0.0426)	(0.0524)
dblue	0.0368	0.0478	0.0964	0.1040*
	(0.0739)	(0.0980)	(0.0603)	(0.0582)
dwifi	0.2072**	0.0341	0.1888***	0.1133*
	(0.0993)	(0.1005)	(0.0660)	(0.0634)
lnSlots	0.2077	-0.0949	0.3065***	0.2902***
	(0.1294)	(0.2872)	(0.1059)	(0.0948)
dcradle	0.0715	-1.0126**	0.1119**	0.0831*
	(0.0565)	(0.3900)	(0.0516)	(0.0498)
dbiometrics	0.1700	-0.4514*	0.1611	0.0817
	(0.1518)	(0.2480)	(0.1172)	(0.1243)
dcamera	0.1261	-0.3375	0.2300**	0.2699**
	(0.1231)	(0.3286)	(0.1079)	(0.1199)
dpagerdata	-0.1090	-0.6644***	-0.0090	-0.0061
	(0.1526)	(0.2401)	(0.1817)	(0.1373)
dlipoly	0.3779***	0.9290	0.3367***	0.2292**
	(0.1101)	(0.5671)	(0.1028)	(0.1002)
dnimh	0.1035		0.1225	0.1294**

	(0.0673)		(0.0814)	(0.0615)
dbliion	0.2917***	0.6523	0.3396***	0.1736**
	(0.0958)	(0.5856)	(0.0878)	(0.0813)
dservicefees	0.5155***		0.3949**	0.4909***
	(0.1384)		(0.1799)	(0.1475)
d2000	-0.1529***		-0.3869**	0.4359
	(0.0487)		(0.1493)	(0.3300)
d2001	-0.3974***		-0.8517***	-0.0724
	(0.0699)		(0.2788)	(0.3558)
d2002	-0.8335***		-1.5323***	-0.7010
	(0.1095)		(0.3793)	(0.4229)
d2003	-1.2281***		-2.1247***	-3.0292***
	(0.1345)		(0.4840)	(0.7904)
d2004		0.0855	-2.4090***	-3.3817***
		(0.1375)	(0.6043)	(0.7377)
Age	0.0731*	-0.2167	0.0370	0.0281
	(0.0385)	(0.1590)	(0.0279)	(0.0331)
constant	2.8712**	-6.9873*	1.7490**	0.8000
	(1.4318)	(4.1381)	(0.7810)	(0.7908)
Casio	0.1139	0.3403	0.1816	0.2718**
	(0.1276)	(0.2190)	(0.1268)	(0.1080)
Compaq	-0.0112		-0.0096	0.1471
	(0.1119)		(0.1305)	(0.1371)
Dell	-0.1183	-0.9222***	0.0596	-0.0034
	(0.1778)	(0.3327)	(0.1887)	(0.1972)
Handspring	-0.2496**		-0.5930*	-0.4519
	(0.1047)		(0.3003)	(0.3184)
IBM			-0.3172	-0.2453
			(0.2975)	(0.3109)
Palm	-0.2574***	-1.9709**	-0.4823	-0.4560
	(0.0946)	(0.7410)	(0.2929)	(0.2892)
Psion	0.0779		0.1515	-0.1877
	(0.2076)		(0.1946)	(0.1933)
RIM	0.2720*		0.2658*	0.3047**
	(0.1409)		(0.1590)	(0.1418)
Sharp	0.0429		0.1625	-0.1954
	(0.1924)		(0.1881)	(0.1940)
Sony	-0.4765***	-3.8458***	-0.9556***	-1.0373***
	(0.1741)	(0.7282)	(0.3348)	(0.3042)
Toshiba	0.0592	0.7750**	-0.0354	0.1074
	(0.1314)	(0.3575)	(0.1179)	(0.1338)
time_RAM			-0.0243**	
			(0.0118)	
time_Flash			0.0512**	
			(0.0208)	
time_Screen			0.1918*	
			(0.1007)	
d2000_Screen				-0.3890
				(0.3074)
d2001_Screen				-1.1074***
				(0.2825)
d2002_Screen				-0.7465*
				(0.3998)
d2003_Screen				0.0979
				(0.5849)
d2004_Screen				0.4697
				(0.5879)
d2000_BatLifee				-0.1066***
				(0.0302)
d2001_BatLife				-0.0407
				(0.0399)
d2002_BatLife				0.1133***
				(0.0366)
d2003_BatLife				0.1501*
				(0.0901)
d2004_BatLife				0.0992**
				(0.0491)
d2000_Weight				-0.9928***
				(0.3091)
d2001_Weight				-0.5139**
				(0.2132)
d2002_Weight				-0.5520**

				(0.2588)
d2003_Weight				-0.6330
				(0.5534)
d2004_Weight				-0.6995**
				(0.2899)
d2000_Volume				0.9430***
				(0.2955)
d2001_Volume				0.9506***
				(0.2381)
d2002_Volume				0.5779**
				(0.2301)
d2003_Volume				1.0873***
				(0.4133)
d2004_Volume				1.1502***
				(0.3068)
N	170	63	203	203
Adjusted R^2	0.8356	0.9102	0.8529	0.8753
RMSE	0.1827	0.1504	0.1762	0.1623
VIF	12.34	85.44	34.03	144.60

See notes to Table 5

Table 7: PDA Price Indexes

Year	Matched Model	Indicator Variable Pooled	Indicator Variable Time Indicators	Characteristics Prices Pooled	Characteristics Prices Time Indicators	Complete Hybrid Pooled	Complete Hybrid Time Indicators
1999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2000	0.918	0.860	0.834	0.847	0.912	0.871	0.910
2001	0.761	0.609	0.589	0.613	0.646	0.653	0.672
2002	0.566	0.353	0.354	0.359	0.371	0.407	0.389
2003	0.428	0.262	0.260	0.269	0.313	0.304	0.323
2004	0.355	0.225	0.223	0.238	0.305	0.274	0.304
AAGR	-18.75%	-25.81%	-25.95%	-24.98%	-21.14%	-22.82%	-21.17%

Note: price indexes reflect adjustments for the difference in time periods between “annual” observations; see [6].