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Getting Smart About Phones: New Price Indexes and the Allocation of Spending Between Devices and Services Plans in Personal Consumption Expenditures

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ABSTRACT

This paper addresses two measurement issues for mobile phones. First, we develop a new mobile phone price index using hedonic quality-adjusted prices for smartphones and a matched-model index for feature phones. Our index falls at an average annual rate of 17 percent during 2010-2018, close to the rate of decline in the price index used in the GDP Accounts. Given relatively flat average prices over this period, our index points to substantial quality improvement. Second, we propose a methodology to disentangle purchases of phones and wireless services when they are bundled together as part of a long-term service contract. Getting the allocation right is especially important for real PCE because the price deflators for phones and wireless services exhibit very different trends. Our adjusted estimates suggest that real PCE spending currently captured in the category Cellular Phone Services increased 4 percentage points faster than is reflected in published data.

KEYWORDS: Smartphone, mobile phone, cell phone, price indexes, quality adjustment, hedonic indexes, personal consumption expenditures

1. Introduction

Since the introduction of the iPhone in 2007, smartphones have become one of the wonders of the modern age, providing a level of connectivity, data access, and functionality that was considered science fiction even ten years earlier.[1] Moreover, smartphones have become far more capable during the past decade, with an iPhone X having about 7 times as many transistors as the original iPhone (and about 51,000 times as many transistors as an early 1980s IBM personal computer).[2] As with many other information and communications technologies (ICT), that rapid change in capabilities and characteristics poses challenges for estimating quality-adjusted price indexes.[3] Accurate estimates of quality-adjusted prices are crucial inputs for measures of inflation, real GDP and productivity growth, capital stocks, as well as for gauging the pace of innovation in the technology sector.[4]

Moreover, until recently, many mobile phones[5] were purchased as part of a bundle; purchasers would receive a subsidy or discount on the phone reducing the upfront out-of-pocket cost in exchange for a commitment to a multi-month wireless service plan

[1] Following Byrne and Corrado (2015), we define smartphones as "cellular phones with powerful operating systems that allow multi-tasking and installation of third-party applications." We also follow IDC's definition of mobile phones "as a device with a screen size of less than 7.0 inches as well as out-of-the-box cellular voice telephony with an in-built mic/speaker, capable of connecting to a cellular network for voice communication through a service provider plan." These definitions exclude tablets, non-telephony enabled devices, and rugged devices.

[2] According to CNet (2018), the A12 chip powering an iPhone XS has about 6.9 billion transistors. An entry on Quora (2016) estimated that the processor on an original iPhone had about 1 billion transistors. Hennessy and Patterson (2012) report that an Intel 80286 powering early 1980s IBM PCs had 134,000 transistors.

[3] For discussions of these challenges and ICT examples, see Aizcorbe (2014), Byrne and Corrado (2017), and Triplett (2006).

[4] For discussions, see Byrne, Fernald, and Reinsdorf (2016) and Byrne, Oliner, and Sichel (2017).

[5] We use "mobile phone" and "cell phone" interchangeably. In the period of our study, the terms are essentially synonymous. That is, nearly all mobile phones connect through a cellular network. Exceptions, like satellite phones, are out of scope for our analysis.

whose price would include payment for the remaining cost of the phone.[6] This bundling, when it occurs, is problematic for economic measurement both because a portion of spending on services actually includes payments for phones and because that misallocation could lead to the wrong deflators being applied to the portion of the wireless services spending that actually reflects this spending for phones.

In this paper, we address both of those issues, developing new price indexes for mobile phones and proposing a methodology for disentangling the phone and service portions of spending on wireless services in recent years.

Regarding prices of mobile phones, we know of only a handful of studies that have attempted to construct constant-quality price indexes. For the United States, Byrne and Corrado (2015) developed matched-model indexes for mobile phones and other types of communications equipment. Their mobile phone index was based on a mix of price data—including prices of used phones for the period studied in this paper—and it declined at an average annual rate of 22 percent from 2010 to 2016.

Outside the United States, we are aware of only one published paper that provides price indexes for mobile phones: Watanabe et al. (2010) for Japan. Using their hedonic analysis for the prices for feature phones and smartphones, they found declines in prices of mobile phones of about 13 percent per year over the period from 2002 to 2007. For smartphones, preliminary findings for two studies have also been reported at conferences

[6] Verizon's 2016 annual report provides a description of these bundled plans and their phaseout: "Historically, wireless service providers offered customers wireless plans whereby, in exchange for the customer entering into a fixed-term service agreement, the wireless service providers significantly, and in some cases fully, subsidized the customer's device purchase. Wireless providers recovered those subsidies through higher service fees as compared to those paid by customers on device installment plans. We and many other wireless providers have limited or discontinued this form of device subsidy." Available at: https://www.verizon.com/about/sites/default/files/annual_reports/2016/downloads/Verizon-AnnualReport2016_mda.pdf

and international meetings. Chessa (2016) applied hedonic techniques to smartphone prices in the Netherlands for the 24-month period beginning in Dec. 2013 and found average annual declines of 14 percent; similarly, the hedonic analysis by Karamti and Haouech (2018) for Tunisia for the six-quarter period beginning in 2016Q1 found annual average declines of around 15 percent.

Among U.S. statistical agencies, the Bureau of Economic Analysis (BEA)—as part of the 2018 Comprehensive Revision of the National Income and Product Accounts—adopted the price index from Byrne and Corrado (2015) for mobile phones for equipment investment, personal consumption expenditures, and trade flows.[7] For the Consumer Price Index (CPI), the Bureau of Labor Statistics (BLS) recently implemented two improvements to the traditional matched-model method that they had used for smartphones through the end of 2017. Beginning in January 2018, the BLS began adjusting prices for item substitutions in the index using coefficients from a hedonic regression; beginning in the April 2018 data, the BLS also increased the frequency with which smartphones in the "basket" are refreshed to twice a year. We cannot, however, compare the BLS price index for mobile phones (or smartphones) to other indexes because the index for mobile phones is not reported separately but rather is a component of a broader index for "telephone hardware, calculators, and other consumer information items."

Regarding the disentangling of bundled purchases of mobile phones and wireless service plans, we know of no past effort to separate out the phone and service components of spending on wireless service plans.

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[7] This index is maintained and updated by the Federal Reserve Board and is available at https://www.federalreserve.gov/releases/g17/commequip_price_indexes.htm.

Our approach to these issues is as follows. On price indexes, we believe that it is important to see if hedonic techniques yield similar or different price trends than past studies. Accordingly, we develop new estimates for the United States of quality-adjusted prices for smartphones using data from IDC (International Data Corporation). These data track average selling prices and units for smartphones and have not previously been used to develop hedonic price indexes. Our preferred hedonic index—which allows coefficients to vary over time—declines at an average annual rate of about 16 percent per year from the first quarter of 2010 to the first quarter of 2018. In addition, we combine our smartphone price index with a matched-model price index for "feature" phones to obtain an overall price index for mobile phones, which falls 17 percent per year from 2010 to 2018Q1.[8] These estimates provide useful points of comparison with other recent estimates of prices, including the index used by the Federal Reserve for the Industrial Production data (which closely tracks Byrne and Corrado (2015)). The price index for mobile phones developed here falls rapidly like the index in Byrne and Corrado (2015) but 4 percentage points slower in the overlap period. Yet, it has the appeal of higher frequency (quarterly versus annual) and direct measurement of the price of new phones whereas the Byrne and Corrado index relied on prices in the market for used phones. This index points to rapid technical change in smartphones since 2010, broadly in line with the

[8] To the extent that our preferred index differs from the deflators used in the national accounts, such differences likely would have limited implications for real GDP because smartphones largely are produced outside the United States. Federal Reserve Board estimates, based on Byrne and Corrado's (2015) reading of Census data and private sources, show U.S. mobile phone production averaged around only $300 million a year from 2010 to 2016. At the same time, some recent research has highlighted that a considerable part of the value added of iPhones and some other products should be attributed to the United States rather than the country from which they are imported. If that adjustment were made, then our estimates could have more significant implications for real GDP and productivity. See Guvenen, Mataloni, Rassier, and Ruhl (2017).

double digit rates of advance for some other digital products as reported in Byrne, Oliner, and Sichel (2017) and Byrne and Corrado (2017).[9]

With regard to the allocation of spending between cellular equipment and services in PCE, we propose two adjustments to separate equipment and services. First, we use Service Annual Survey (SAS) data to identify upfront or out-of-pocket spending on phones that is included in the services category. Second, we use a comparison of phone prices from IDC and J.D. Power to gross up equipment spending to the full cost of the phone, taking account of any subsidy offered by the service provider in exchange for a commitment to a long-term contract for cell service. In particular, the IDC data tracks the price of smartphones without any service commitment; that is, without netting out any discounts (or subsidies) to the up-front cost of the phone. In contrast, the J.D. Power data—which are based on consumer surveys—capture the up-front or out-of-pocket price paid net of any subsidies. Accordingly, the difference in prices across these datasets provides an estimate of the size of the subsidy. This comparison indicates that these subsidies were quite substantial prior to 2013, in the range of $200 to $300. Then, starting around the beginning of 2013, mobile phone providers began more frequently offering straight up purchase options without these discounts on purchasing a device. These subsidies or discounts largely, though not entirely, had disappeared by 2018.

With this information on discounts in hand, we can split out the portion of spending on wireless service plans that actually reflects spending for phones. We find that this share averaged 28 percent from 2010 to 2017, hitting a high of more than 36

[9] Price trends provide information about the pace of innovation via the "dual" relationship in which price changes reflecting changes in input costs and total factor productivity. That being said, swings in margins and other factors may complicate the linkage between price trends and the pace of technological advance.

percent in 2012 and falling to about 21 percent in 2017. And, we can then apply our deflator for phones to this portion of spending to get an adjusted estimate of an overall deflator for the spending on Cellular Telephone Services and, by implication, for real PCE for this category.

Our calculations indicate that, after making these corrections, the deflator for Cellular Telephone Services fell at an annual average rate of 7.7 percent from 2010 to 2017, about 4 percentage points faster than the currently published deflator for this category. Accordingly, real PCE for this category has grown 4 percentage points faster per year over this period than the currently published series.

We believe our results are valuable in their own right as a contribution to improved measurement of prices and PCE. In addition, our results contribute to the growing literature that documents the rapid technical change in and diffusion of products related to the digital revolution.

This paper is organized as follows. Section 2 discusses the IDC data we use and highlights the rapid improvement of smartphone characteristics. We describe our methodology for estimating quality-adjusted price indexes in Section 3, and our new results for smartphone and overall mobile phone price indexes in Section 4. Section 5 describes how we use data from the SAS and a comparison of price data from IDC and J.D. Power to disentangle and allocate spending on phones and services when the two are bundled together. Section 6 concludes.

2. IDC Data and Smartphone Characteristics

IDC Data

We rely on data from IDC to develop smartphone price indexes. Specifically, we use data from the Worldwide Quarterly Mobile Phone Tracker dataset published by IDC (International Data Corporation). IDC estimates revenue, units, and prices by model for the U.S. market using public and proprietary information from phone manufacturers, component suppliers and distribution channel companies (e.g. retailers and wholesalers).[10] Unique models are distinguished in the data by four variables: the "model" in IDC nomenclature (e.g. "iPhone 4s"), the size of internal storage (e.g. 8 gigabytes), the mobile telecommunications generation (e.g. 3G), and the operating system (e.g. "Android Jelly Bean 4.1"). The database contains both consumer and commercial sales and does not provide model-level information by market, so we cannot produce a pure consumer price index; however, roughly 90 percent of the unit sales in the database are to the consumer market. There are 1,294 phone models in the database.

The model prices reported are average selling prices (before point-of-sale taxes) offered by retailers or service providers *without a contract commitment*, including channel costs such as freight, insurance, shipping, and tariffs. As noted above and discussed below, it was common during a portion of the period covered in our analysis for service providers to bundle phones with service contracts, and the IDC dataset indicates over 80 percent of phones were sold through service providers in this period. A

[10] Data sources used by IDC are briefly described in "Worldwide Quarterly Mobile Phone Tracker", available at https://www.idc.com/getfile.dyn?containerId=IDC_P8397&attachmentId=47322790. The description of methodology in the text is based on "IDC's Worldwide Mobile Phone Tracker Taxonomy, 2018," which is only provided to subscribers, and on conversations with IDC analysts.

crucial feature of the dataset is that for phones sold through carriers, IDC analysts have been successful in collecting the price charged for each phone model *without a contract commitment*; that is, in all cases where phones were sold with a service contract commitment, the price recorded was the price for that model of phone, without contract, directly reported by the carrier. We also confirmed that IDC is collecting actual prices paid, rather than manufacturers' suggested retail prices (MSRPs), by examining cases where a prominent manufacturer publicizes MSRPs and confirmed that prices do, in fact, appreciably deviate from the MSRP. In a small number of cases, we recoded price observations to eliminate implausible patterns.[11]

Smartphone Characteristics

The IDC database also provides detailed information on phone model characteristics spanning 2010Q1 to 2018Q1. Table 1 reports values of key smartphone characteristics in the IDC data. The main inference we draw from these data is that the quality of smartphones improved significantly over the sample period. For example, processor speed increased at an average annual rate of 9 percent between 2010 and 2017, while the average number of cores in a phone's processor rose from 1 in 2010 to over 5 by 2017. Storage capacity also rose very rapidly, increasing at an average annual rate of 29 percent during 2010 to 2017, and the amount of working memory (RAM) increased at

[11] In particular, we applied two rules. In cases of apparent missing values, defined as quarters where no units of a model were sold flanked by non-zero sales in both adjacent quarters, a price and a quantity were added using log-linear interpolation. In cases of a price spike, defined as a price increase of 10 percent or more in one quarter followed by a price decrease of 10 percent or more in the following quarter, or a price "pothole," defined symmetrically to spikes, we substituted the log-linear interpolated price for the reported price.

an average annual rate of 33 percent during this period. Camera resolution also improved at a good clip during this period.

During our sample period, other important aspects of the market for mobile phones changed. The share of smartphones in the overall market for mobile phones rose from 38 percent in 2010 to 94 percent in 2017. And, market concentration in the market is substantial and climbs over this time period. The Herfindahl index calculated with manufacturers' revenue shares in the consumer smartphone market is 0.16 in 2010 and climbs to 0.44 by 2017.[12]

3. Methodology for Quality-Adjusted Price Indexes[13]

Matched-Model Indexes

We estimate both matched-model and hedonic price indexes to control for quality change though we emphasize hedonic indexes. The matched-model approach, the most common method employed by statistical agencies, relies in its most basic formulation on price changes over time for specific models of the good in question, holding quality constant by construction if models are specified in enough detail. This approach takes an average of price changes for specific models rather than calculating the change in the price average across models. Although the matched-model approach ideally strips out the effect of quality change on prices, this technique may fall short in cases characterized by frequent model entry and exit for two reasons. First, in the period of entry, no price change relative to the previous period is available, and, of course, no price change is

[12] There were 23 manufacturers in the market in 2017. If each manufacturer had an equal share of the market, the Herfindahl index would be 0.05.
[13] The description of hedonic methodology in this section draws heavily from Byrne, Oliner, and Sichel (2018), including a significant amount of text taken and adapted directly from that paper.

available in the period following the model's exit either. Second, if entering models have a lower price relative to quality than incumbent models and do not drive down the price of incumbent models—that is, the law of one (quality adjusted) price does not hold—before the older model exits the market, the quality improvement represented by the new model may not be reflected in the index. Both issues are a concern in the market for mobile phones.

For matched-model indexes, we consider first an index constructed as an unweighted geometric mean of price changes, known as the Jevons formula. We start with unweighted indexes because statistical agencies typically do not collect weights at the model level in each period.[14] In addition, researchers estimating hedonic indexes often do not have model-level weights.

Such a lack of weighting raises two issues. First, some models undoubtedly represent a greater share of the market than others—a particular concern in the mobile phone market where a handful of Apple models account for a disproportionate share of the market. Second, the relative importance of models changes over time. The importance of the issue of fixed weights in price indexes has been the subject of extensive research. Generally speaking, allowing weights to evolve over time is the preferred approach as that allows the index to reflect consumers' response to relative prices and substitution across models as discussed in Diewert (1998). Our second matched-model index addresses this issue; we calculate an index where the model-

[14] Survey participants may be asked to report a revenue-representative set of products when they first enter the survey sample, but then not be asked to report sales by model in subsequent periods.

specific price changes are weighted by the average of their revenue share in the two periods used to calculate the price change (known as the Tornqvist formula).[15]

Hedonic Price Index Methodology

Hedonic regression—estimating the statistical relationship between model prices and product characteristics and performance—provides information that can be used in a variety of ways to construct constant-quality indexes. One can impute model prices for the period prior to the model's appearance in the market and use the implied price change in a conventional matched-model formula (Pakes, 2003). Another approach is to adjust the price of a newly-introduced model according to the implicit valuation of the difference in characteristics relative to an existing model.[16] In this paper, we focus on a third approach, estimating "time-dummy" hedonic price indexes. In this setup, product characteristics act simply as control variables and the focus is on the quality-adjusted price trend implied by the coefficient on the dummy for each time period, with the quality change stripped out by the regression.[17] All of these approaches are valid uses of hedonic regression for the construction of constant-quality price indexes, and the choice of method is dictated largely by the circumstances.[18]

To fix ideas for our time-dummy hedonic price indexes, consider the following simple dummy-variable hedonic specification:

$$\ln(P_{i,t}) = \alpha + \sum_k \beta_k X_{k,i,t} + \sum_t \delta_t D_{i,t} + \varepsilon_{i,t} \qquad (1)$$

[15] The Tornqvist index satisfies the criteria set out in Diewert (1976) for a "superlative" price index—one which provides a reasonable approximation to a true cost of living index.

[16] This "explicit quality adjustment" approach is used by BLS in their consumer price index for smartphones. (See "Measuring Price Change in the CPI: Telephone hardware, calculators, and other consumer information items," available at https://www.bls.gov/cpi/factsheets/telephone-hardware.htm.)

[17] The BLS used this approach for the first time for their producer price index for semiconductors beginning in 2018.

[18] Triplett (2006) notes these approaches are equivalent under fairly general conditions.

where $P_{i,t}$ is the price of smartphone *i* in period *t*, $X_{k,i,t}$ is the value of characteristic or performance metric *k* for smartphone *i* in quarter *t* (measured in logs or levels, as appropriate), $D_{i,t}$ is a time dummy variable (fixed effect) that equals 1 if smartphone *i* is observed in quarter *t* and zero otherwise, and $\varepsilon_{i,t}$ is an error term.

An often-cited concern with equation 1 is that the coefficients on the characteristic or performance variables are constrained to remain constant over the full sample period as discussed in Berndt (1991) and Pakes (2003). We mitigate this concern by estimating each time dummy with a separate regression; that is, we estimate adjacent-period regressions as discussed in Triplett (2006).[19] Specifically, we estimate the following regression for each overlapping two-quarter period:

$$\ln(P_{i,t}) = \alpha + \sum_k \beta_k X_{k,i,t} + \delta D_2 + \varepsilon_{i,t} \qquad (2)$$

where $P_{i,t}$ is a price observation for smartphone *i* in quarter *t*. The dummy variable D_2 equals 1 if the price observation is in the second quarter of the two-quarter overlapping period and 0 otherwise. In addition, we run weighted regressions, where observations are weighted according to the share of revenue the models represent in the market during the quarter when each price is observed. To construct a price index from this sequence of regressions, we spliced together the percent changes implied by the estimated coefficients on the D_2 variables.[20]

[19] An alternative approach, advocated by Pakes (2003), is to run a separate regression for each period and construct a price index using imputed prices for each period.

[20] We apply the adjustment suggested by van Dalen and Bode (2004) for adjacent-period regressions to correct for bias introduced when going from the natural log of prices to price levels, which is based on the standard error of the estimated coefficient on the second-period dummy. The adjustment reduces the annual average rate of decline for our preferred index by 0.1 percentage point over the period of our study.

4. Smartphone Price Indexes

Matched-Model

Price indexes constructed using different formulas and specifications with the IDC data are shown in table 2. As shown in line 1, the simple average price of smartphones—with no quality adjustment—edged down about 1 percent per year on average in the time period of our analysis, from the first quarter of 2010 to the first quarter of 2018. Roughly speaking, there are two noticeable periods—prices moved up through 2013, then fell, on balance, through 2017—a pattern visible in the quality-adjusted price indexes as well. The trend in the unweighted Jevons index, line 2, contrasts sharply with the path of average prices; the index falls 19 percent per year on average. Line 3 reports results for the revenue-weighted Tornqvist index. Clearly, weights matter a great deal for this market: the weighted index falls 10 percent per year on average, a full 9 percentage points more slowly than the Jevons index. Numerically, we attribute this difference to a prominent phone manufacturer which has a substantial market share by revenue but releases relatively few phone models and consequently plays a more important role in the Tornqvist index than it does in the Jevons index.[21] Phone models sold by this manufacturer have significantly slower price declines than those of other producers, on average. Accordingly, we weight price observations in the hedonic regressions we report below by model revenue for the relevant quarter.

[21] Our agreement with the data provider prevents us from disclosing the name of the manufacturer.

Hedonic

For our hedonic indexes, we first consider the simple, time-invariant specification in equation (1), regressing (the natural log of) price on four continuous measures of engineering capability (storage capacity, screen size, camera resolution, and processor speed, all in natural log form) and an array of dummy variables.[22] Specifically, we include dummies for phone manufacturer (there are 43 in our dataset), for operating system (there are 58 in our dataset, for example, "Android Froyo 2.2"), for telecommunications generation (2G, 3G, 3.5G, 4G) and for input type (QWERTY keyboard vs. touchscreen). We also include a dummy for models in their quarter of introduction.

Our rationale for including an introduction-quarter dummy is to account for price variation over the model life-cycle that does not merit inclusion in measured quality-adjusted price trends. In particular, prices paid when models are first introduced may be affected by a number of factors that confound quality adjustment: When a model first appears, the novelty of the item may lead select early-adopter consumers to pay a premium for the item that does not persist over time.[23] Alternately, the market may be in disequilibrium at first in the sense that the "law of one price" does not hold and the new item is sold at a lower quality-adjusted price than incumbent models (put another way, the price of the old model does not fall enough to equilibrate to the price-performance

[22] We also experimented with including measures of smartphone performance from Passmark, following the emphasis in Byrne, Oliner, and Sichel (2018) on using performance measures in hedonic regressions. Our experimentation with a small set of models indicated that performance measures added relatively little once a full set of characteristics were included. Though we plan to pursue the approach further in future work, we did not do so in the current paper, and we do not report results from hedonic regressions using performance measures.

[23] This phenomenon was first studied in Pashigian, P., B. Bowen, and E. Gould (1995) for the motor vehicle market. See Aizcorbe, Bridgman, and Nalewaik (2009) and Williams and Sanger (2018) for more recent discussions.

ratio of the new model).[24] Or, very early buyers may demand a discount in exchange for bearing the burden of testing the new features of the phone.[25] In addition, Apple typically introduces new models in September—the third month of the third quarter—implying that the average price observed in the IDC data for that quarter is not an average of three full months of price history as for other quarters, and that difference may distort estimates of the price change in the following quarter. Whatever the correct explanation, we find that adding a dummy variable for the first quarter a model appears in the market has a noteworthy impact on our results as discussed below.

To recap, the first hedonic regression we report includes quarterly time dummies, variables for engineering capability, dummy variables for manufacturer and operating system, and a dummy for the quarter a model is introduced in the market. As shown on line 4, the price index constructed by chaining the coefficients on the quarterly dummies falls 19.6 percent per year, on average, from 2010Q1 to 2018Q1. The regression results indicate this set of variables explains 83.9 percent of the variation in price.

We next consider the impact of allowing the effect of these characteristics on price to vary over time using the adjacent-quarter regressions in equation (2). For example, a particular mobile telecommunications generation (2G, 3G, 4G) will represent relatively high quality when first introduced and relatively low quality once the succeeding generation enters the market. Thus, one might expect a positive coefficient on 3G early in its life cycle and a negative coefficient once 4G phones are available. Likewise, when phones with the Android Ice Cream Sandwich operating system appeared, they commanded a premium over phones with Android Gingerbread, the

[24] Cole et al. (1986) offer this explanation in the market for computers.
[25] We thank Erick Sanger for suggesting this explanation.

predecessor operating system; once its successor—Android Jelly Bean—appeared, Ice Cream Sandwich phones sold at a discount. Dummies for these fine gradations of operating system have the added appeal of serving as proxies for an array of small features that are enabled by each operating system generation. This specification yields a price index—reported on line 5—that falls 15.5 percent on average, appreciably slower than the index derived from the regression with time-invariant coefficients. This set of adjacent-quarter regressions explains 92.3 percent of price variation on average across the time period, substantially more than in the time-invariant regression. For the reasons discussed below, this is our preferred specification. And, in this specification, the dummy for quarter of model introduction matters; when we exclude this dummy from this specification, the aggregate price index falls 2.6 percentage points slower per year on average.

We also experimented with separate adjacent-quarter regressions for each of the six phone manufacturers which accounted for 5 percent or more of the market by revenue in at least one quarter (Apple, Blackberry, HTC, LG Electronics, Motorola, and Samsung) and a seventh regression for the residual manufacturers. These separate manufacturer regressions also introduce yet another form of flexibililty – characteristic effects are permitted to vary across manufacturers. The resulting price indexes vary tremendously across vendors, ranging from a 12 percent to 29 percent annual average decline during 2010 to 2018. Aggregating these price indexes using revenue weights yields a price index—shown on line 6—that falls 16.0 percent per year on average. Because this rate of decline is roughly the same as that for the regression which pools manufacturers—reported on line 5—and because the pooled price index is somewhat more precise, we prefer the pooled regression shown on line 5.[26]

Table 3 presents an overview of the regression results for our preferred specification—the adjacent-quarter specification run with revenue-weighted observations. As shown in the upper panel, individual adjacent-quarter regressions have 417 model observations on average, and no regression has fewer than 145 observations. The regressions explain 92 percent of price variation on average, as measured by the r-squared statistic, and no regression has an r-squared below 0.88.

The middle panel highlights that, among the continuous performance variables, internal storage and camera resolution are statistically significant as control variables at the 10 percent level in 31 out of the 32 adjacent-quarter regressions. Screen size and processor speed are significant in 25 and 23 out of the regressions, respectively. As noted previously, in this hedonic approach, model characteristics are treated as control variables and their estimated sign and magnitude are difficult to interpret.[27] That being said, we note that coefficients for all four of the performance variables are positive, both on average as shown in the table, and in all cases where the coefficient estimate is significant. The model-introduction quarter dummy variable discussed above is significant in 19 of 32 regressions, negative on average, and negative in 14 of 19 cases where the variable is significant.

[26] The regression which pools all manufacturers is more precise in the sense that 22 of 32 quarterly time dummy coefficients are significantly different from zero at the 90 percent level in contrast to the manufacturer-specific regressions, for which the number of significant time dummies ranges from 4 to 11. Note that because our data covers the entire population of mobile phone models, p-values reflect population dispersion, rather than sampling variation.

[27] Although the full vector of characteristics coefficients can be used to quality-adjust individual prices, we view the common practice of informally considering coefficients on individual characteristics as implicit prices as ill advised. Pakes (2003) notes that "the hedonic regression is a "reduced form," that is, its coefficients have no obvious interpretation in terms of economic primitives."

The lower panel summarizes results for other discrete variables. In nearly all of the regressions, at least one operating system and manufacturer dummy was significant—28 and 30 cases, respectively. There are 54 distinct operating system versions in the data, but only a handful are relevant in any particular adjacent-quarter regression.[28] Although on average, only 5.4 of these have significant coefficients in each regression, 39 of the 54 dummies are significant at least once. Similarly, 6.7 of the 41 manufacturer dummies are significant on average. The dummy variables for input type and for mobile generation play a role less frequently, with at least one of these dummies statistically significant in 12 and in 5 regressions respectively. To provide additional background on our results, Table A1 in the Appendix shows complete regression results for two selected quarters for our preferred specification.

Bottom line: our preferred specification delivers a price index that falls at an average annual rate of 15.5 percent from 2010:Q1 to 2018:Q1.

We also created an index using the IDC data on feature phones (i.e. mobile phones that aren't smartphones). The database does not provide model-level information for feature phones, but does allow us to construct a matched-model index using average prices for narrowly defined groups of phones.[29] Our feature phone price index falls at an average annual rate of 18.5 percent during 2010 to 2018 as shown in a memo item in table 2. We created a Fisher chain-aggregated index for all mobile phones using this feature phone index and our hedonic smartphone index—also shown in the table—which

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[28] The count of operating systems in our sample is 17 Android, 9 BlackBerry, 9 iOS, 8 Windows Mobile, and 11 miscellaneous others.

[29] The characteristics used to define narrow our narrow groups of phones are manufacturer, form factor (clamshell, bar, etc.), storage, generation, camera resolution, GPS capability, primary memory card, color display, and input type (QWERTY, touchscreen, etc.).

falls at an average annual rate of 16.6 percent. This rate of decline is similar, but 4 percentage points slower than that of the Byrne and Corrado index—reported in the memo item in table 2—that currently is being used by the BEA for mobile phones. We prefer our new index to the Byrne and Corrado index because the new index relies on prices for new phones rather than used phones, draws on data with broader coverage, has revenue weights, and uses quarterly rather than annual observations.

5. Allocation of PCE Spending Between Cellular Devices and Bundled Service Contracts

An improved price index is useful for proper deflation of nominal spending on mobile phones as recorded in PCE. However, in the NIPAs, nominal spending for mobile phone purchases is not reported in a single category. Although the PCE category "telephone and related communication equipment" includes purchases at retail outlets, the bulk of mobile phones purchased in the past decade were obtained directly from wireless carriers. Moreover, for reasons that we detail below, the value of those phones ends up misreported in PCE for Cellular Telephone Services.

In this section, we propose a method to identify the component of PCE for Cellular Telephone Services that represents spending on mobile phones. Extracting this component entails two corrections. First, we use data from the Census Bureau to identify the upfront cost of phones paid by purchasers. As described below, this reported upfront spending on phones does not represent the full cost if the phone was subsidized by the service provider. Accordingly, our second correction makes a further adjustment to account for these subsidies so that the full cost of the phone is captured as equipment spending at the time of purchase. This method corrects the misallocation of some phone purchases as services and thereby provides a way to apply the appropriate deflators to each category of spending.

Accounting for the Upfront Cost of Phones

There are two potential data sources that could be used to estimate the upfront cost of phones (that currently is counted within the services category in PCE): both the Census Bureau's Service Annual Survey (SAS) and the quinquennial Economic Census provide some information on the detail underlying the top line estimate for total revenues of wireless service providers. In addition, because respondents to these surveys typically follow the accounting rules that they use in their annual reports, annual reports contain useful corroborating information. To sort through these accounting issues, we begin by considering how some hypothetical transactions are recorded in the annual reports, the SAS survey, and in the quinquennial Census.

We illustrate the accounting underlying these transactions by considering four ways that one could have acquired an Apple iPhone 3G at introduction. Our first scenario considers a purchase of the phone at a subsidized price with a commitment to a two-year service contract, and the second considers an outright purchase of the phone. Apple's initial announcement offered two prices: $199 if one was willing to commit to a two-year contract with AT&T, and $499 if one did not commit to the contract. In these types of contracts, the $199 was commonly referred to as the subsidized price to reflect the fact that the service provider had held down the upfront cost of the phone. Because the accounting convention used by service providers in their annual reports was to record revenues as they were received, the cost of the phone (whether $199 or $499) was recorded in the SAS and in company annual reports as equipment revenue in the year the purchase was made.

What about the monthly payments for wireless service in these two scenarios? When consumers entered into (typically two-year) contracts with the carriers, the providers would attempt to recoup the gap between the full and subsidized prices ($499 vs $199), by elevating the monthly amount paid for wireless service over the course of the contract. In our example, suppose that this raised their monthly charge by $12.50 so that consumers that signed a contract made (inflated) monthly service payments of $62.50 for two years for services, whereas consumers that paid for the phone up front only paid $50 per month for services.[30]

The first two rows of table 4 compare how spending for equipment and services would be recorded in each of these two scenarios. In service-provider annual reports, the revenue recorded for those that paid the full cost of phone up front (line 2 of the table) correctly includes the $499 for the phone as equipment and the monthly charges that only cover services as service revenue. For those that sign a contract (line 1), providers recorded part of the full cost of the phone—the upfront piece—as equipment revenue. But a convention prevalent through the end of 2017 was to report the additional cost of the phone paid in the elevated monthly service bill as service (not equipment) revenue. So, in this example, the $12.50 boost to monthly service bills that covers the cost of the phone is reported as revenue for services. That is, this practice would inappropriately allocate revenues received for the phone as services. Moreover, it also affected the

[30] We assume the service provider recoups the unpaid portion of the non-contract price of the phone over the duration of the service contract. The service provider may ultimately recover less (or more) than the price for purchasing the phone outright (the IDC price) if, say, the price elasticity of demand differs systematically between customers who pay the full price up front and those who do not.

timing for recording the phone purchase: only the upfront cost was reported on the day of the transaction, the other revenues collected over the service contract were spread over the span of the contract.

As shown in line 3, the accounting treatment when a consumer purchases the phone though an installment plan is the same as when consumers pay the full cost of the phone up front (line 2); the annual reports accurately exclude any payments for phones from service revenues. Similarly, line 4 shows the case where consumers purchase their phone at a retail outlet not affiliated with the carrier (like Best Buy) and sign up for wireless services separately. Again, the service revenues reported by providers correctly only includes consumer payments for the services; the purchase of the phone is recorded separately in Best Buy's financial statements.

We confirmed that numbers reported in the annual reports lined up with those in the SAS survey. In the annual reports, firms report revenues received from equipment sales separately from service sales in a line item typically called "equipment revenue" in their income statements. Similarly, in the SAS survey, detail on the sources of revenues includes a line item called "Reselling services for telecomm equipment, retail" that gives the dollar value of equipment sales as reported by the carriers.[31] To see if these two series are capturing the same spending, we compare the ratio of equipment to total revenue in the annual reports to the ratio of SAS reselling revenues to total revenues. In 2012, for example, the ratios from the annual reports for the top four carriers, Verizon,

[31] The coverage of this line in the SAS survey is broader than we would like in that it includes sales to all subscribers—not just consumers—and for all types of equipment—not just phones. We do not view the product coverage issue as a big problem because most of this spending is on phones and carriers only more recently began reselling tablets and other equipment.

AT&T, Sprint and T-mobile, were either 10 percent or 11 percent. In the SAS survey, the ratio of reselling revenues to total revenues was 11 percent that year.

So, again, for purchases that involve a contract, the SAS survey reports the $199 upfront cost of the phone as equipment and all other payments received on a monthly basis (including the part that covers the phone subsidy) as service revenue.

As in the SAS survey, the top line revenue estimate for wireless service providers in the Economic Census also includes revenues for equipment. However, unlike the SAS survey, the Economic Census does not provide a separate line item that one could use to split out the equipment revenue from the top line.

This feature of the Economic Census, that all equipment revenue received by wireless service providers is included as service revenue, has important implications for nominal PCE because in Census years, the level of nominal PCE for wireless services is set to match that in the Economic Census. Specifically, for Census years, BEA estimates current dollars for this category by applying a commodity-flow method to total receipts (business, consumer and exports) reported by wireless carriers in the Economic Census. Those benchmarks are then extrapolated using data on receipts reported by wireless carriers in the Service Annual Survey (SAS). Accordingly, the level of PCE for wireless services includes *all* the revenues received for mobile phones that they sold to subscribers (upfront and other).

Correcting for this problem, however, turns out to be straightforward because of the data described above from annual reports and the SAS survey that isolate the upfront revenue received by service providers for equipment. The relevant calculations are shown in Table 5. The top line shows current estimates of PCE for Cellular Telephone

Service. Lines 2 and 3 are from the SAS survey: total revenues and revenues from reselling the phone equipment. The implied share of equipment to total revenue (line 4) averages just over 13 percent in the period during 2010 to 2017; it increases steadily over the period, rising from a bit over 9 percent in 2010 to 18 percent in 2017.

Adjusting for Subsidies (or "Discounts") on Smartphones

The more difficult problem is teasing out the part of monthly service payments that represent phone purchases. To solve this problem, we combine the IDC price data described above with additional price data from J.D. Power to estimate the discounts/subsidies implicit in the upfront equipment revenue reported by providers. We then use this ratio to form an adjustment factor to the share of equipment to total revenue that we formed from the SAS survey. This adjustment effectively augments the upfront revenues in the SAS data (the $199 in our example) to a non-contract purchase cost basis (the $499).

The IDC data we used above to estimate new price indexes provide average selling prices of smartphones without any discounts (or subsidies). In contrast, consumers surveyed by J.D. Power report the upfront price they paid for their smartphones, net of discounts.[32] Thus, a comparison of prices in the IDC and J.D. Power datasets provides a reasonable gauge of the size of discounts. In our earlier example, IDC dataset would record a price of $499 under all of the four transactions. In other words, units sold with a service contract are recorded by IDC with a price that does not include

[32] The reported price in the J.D. Power data is the respondents' answer to the question: "How much did your current wireless phone cost, including any rebates or cash-back deals received? Your best estimate is fine." Thus, this price reflects any discounts or subsidies received by the consumer.

any cross-subsidy between device and service plan. Note that if the carrier dropped the no-contract price of the phone to $490 the following quarter, this price would be recorded in the IDC database, even if the "marquee" price on the Apple website continued to be $499.

In contrast, the J.D. Power survey reports the upfront price. In our example, prices for transactions that did not involve a contract would be the same as the IDC price, $499. However, in the transaction with a 2-year plan commitment in our example, respondents to the J.D. Power survey would (correctly) report they paid $199 and the survey would record the price as $199. That is, the J.D. Power price is the upfront price that nets out all discounts and subsidies. This difference in price concept allows us to identify the discounts or subsidies that were an important feature of smartphone pricing. Carriers began eliminating discounts in 2013 and, according to press reports, discounts largely—though not entirely—were gone by the end of 2016 and finally disappeared by 2018 as consumers paid for the full price of smartphones up front or had an explicit charge on their wireless bill for installment payments.

To gauge the size of discounts or subsidies, figure 1 plots average smartphone prices from both the IDC and J.D. Power data (which also are reported in table 6). By average prices, we mean the average of reported prices in the datasets prior to any quality adjustment. The difference in trends is stark. The IDC average prices are flat through about 2013 around $500 per phone. Prices then drift down through 2016 before popping back up in 2017 to $460 per phone. The average price in the J.D. Power data is about $160 per phone from 2010 to 2012. In 2013, these prices then begin rising rapidly (right around the time that plans with discounts were beginning to be removed) and by 2016 and 2017 were relatively close to the IDC average prices.[33] Although a portion of the difference in average prices between the datasets could reflect differences in coverage (e.g. a small share of the price observations in the IDC dataset are for sales to business customers), we believe that these differences largely reflect discounts or cross subsidies, and these discounts amounted to about $300 per phone between 2010 and 2012.[34] The removal of these discounts thereafter led to a steep uptrend in average prices as experienced by consumers beginning in 2013. And, to the extent that service providers recaptured those discounts in the prices set for wireless service plans, a substantial amount of spending recorded as for wireless service actually reflects payments for devices.[35]

To correct this understatement of equipment purchases, we use the ratio of IDC to JDPOWER average prices (including "zero" price phones)—shown on line 5 of table 4—as an adjustment factor to the equipment share of revenues reported in the SAS survey.[36]

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[33] The line plotted in figure 1 includes all reported positive or zero prices. Table 4 also reports average prices when observations with a reported price of zero are excluded.

[34] As further evidence of subsidies and their gradual disappearance, Verizon's annual reports indicate that their cost of purchasing wireless phones from manufacturers was *twice* the resale revenue of the equipment reported in 2013 and 2014, when most subscribers had the upfront cost of the phone subsidized. As consumers shifted away from traditional plans towards plans that required them to pay the full cost up front, this gap between the reported equipment cost and resale revenues narrowed significantly: that ratio dropped to 1.17 (from 2.0) by 2017, when the majority of subscribers were on plans that required that they pay the full cost of the phone up front.

[35] That a large amount of equipment revenue from subsidized plans was actually reported as service revenue by firms was highlighted by service providers when the shift from subsidized plans (with a lot of equipment revenue recorded in services) towards no-subsidy plans (with no equipment revenue recorded in services) lowered the service revenues that providers showed in their financial statements. The declines were significant and required explanation. For example, Verizon's 2015 annual report included the following statement about the effect of increases in no-subsidy plans: "The increase in activations of devices purchased under the Verizon device payment program has resulted in a relative shift of revenue from service revenue to equipment revenue and caused a change in the timing of the recognition of revenue. This shift in revenue was the result of recognizing a higher amount of equipment revenue at the time of sale of devices under the device payment program."

[36] One caveat to our results is that the adjustment factor is based on prices for smartphones, whereas the spending is for all mobile phones.

This ratio provides the key piece of information on the relationship between the recorded out of pocket cost of a phone and the actual full cost. Specifically, we multiply the ratio of average prices (shown in line 5) and the equipment share of revenues in line 4 to obtain an adjusted share (line 6). That adjusted share averaged about 28 percent from 2010-2017, rising until 2012, then falling appreciably through 2017, as average phone prices declined and an increasing share of phones were sold at retail outlets, for which only the wireless services would be recorded in the SAS.

We then use the adjusted share from line 6 to allocate spending for Cellular Telephone Service (line 1) into phones and wireless services. As seen in lines 7 and 8, our estimates suggest that a nontrivial share of what is reported as wireless services in PCE represents revenues from equipment sales by carriers.

Real PCE Spending on Phones and Wireless Services

Our derivation of the adjusted deflator and real PCE for spending currently categorized as Cellular Telephone Services is shown in table 7. The new, adjusted index requires expenditure and price indexes for the two components: phones and services. Given the split derived above between phone and service revenues in the PCE Cellular Telephone Services category (lines 1 and 2), we can deflate the phone component using the new price index that we have developed and deflate the service spending using the CPI currently used in the NIPAs, "wireless telephone services."[37]

[37] We believe that falling constant-quality prices for the devices is not already captured by the matched-model methodology used for the CPI for wireless telephone services because the price of service plans collected for construction of the CPI do not vary depending on the device purchased by the customer. Note that explicitly collected installment payments for devices are not included in the CPI for wireless telephone services. (See https://www.bls.gov/cpi/factsheets/telecommunications.htm.)

Our mobile phone price index falls substantially faster than the CPI currently used to deflate spending for mobile phone services; our phone index falls about 17 percent per year, compared with an average 3-1/2 percent decline in the CPI deflator during 2010 to 2017. A new overall deflator calculated as a weighted average of the two indexes yields a new index for Cellular Telephone Services (line 4) that falls about 4 percentage points faster than the deflator currently used in the NIPAs (declines of 7.7 percent compared with 3.5 percent). This difference in deflators translates directly into a mirror image difference in real PCE growth for this category, implying about 4 percentage points of additional real PCE growth when adjusted deflators are used (lines 7 to 9).

For overall PCE, we note that nominal spending on Consumer Telephone Services makes up around one percent of overall PCE over this period. Using this share, our new, adjusted deflator for wireless services implies that the overall PCE deflator increased an average of about 4 to 5 basis point less per year from 2010 to 2017, with a corresponding boost to overall real PCE growth. Our results also imply a small offset of about 1 basis point lower PCE growth from deflating the PCE spending on cell phones recorded in the "telephone and related communication equipment" by our new deflator, which falls more slowly than the price index currently used in the NIPAs.

Although we do not provide estimates for earlier years, our best guess is that our results do not imply *acceleration* of PCE. We have no reason to believe that the share of telecom service provider revenue accounted for by reselling equipment was different prior to the period of our analysis. And, Byrne and Corrado (2015) found that mobile phone prices have declined at similar rates in the past.

5. Conclusion

This paper addresses two problems related to the measurement of smartphones. First, we develop new quality-adjusted price indexes for smartphones using data from IDC that have not previously been used for this purpose. Our preferred index—a hedonic index that allows coefficients on characteristics to change over time—falls at an annual average rate of 16 percent from 2010 to 2018. Combining this hedonic with a matched model index for feature phones yields a price index for mobile phones overall that falls at an average rate of 17 percent. This rate of decline is close to, but about 4 percentage points slower, that in Byrne and Corrado (2015) and to the index currently being used by the Bureau of Economic Analysis since the Comprehensive Revision of the GDP accounts in the summer of 2018.

Second, we develop a methodology for disentangling and correctly allocating spending on phones and wireless services when the two are bundled together, typically with a discount on the upfront out-of-pocket cost of the phone in exchange for a commitment to a multi-year service plan. This bundling causes measurement challenges because the accounting conventions used by wireless service providers led to some equipment purchases being counted as service revenues. We correct this misallocation using detail in the Service Annual Survey. In addition, we use a comparison of price data from IDC and J.D. Power adjust for the subsidies on phones that some purchasers received in exchange for committing to a long-term contract for wireless service. With these changes, the adjusted deflator for the PCE category Cellular Telephone Services fell at an average annual rate of 7.7 percent during 2010 to 2017, about a 4 percentage points faster decline than in currently published measures. Similarly, this adjustment implies faster growth in this category of real PCE by about 4 percentage points. Given the share of this category in overall PCE, our results imply 4 to 5 basis points faster growth in overall real PCE over this period.

Taken together, our results highlight the rapid decline in quality-adjusted prices for products related to the digital economy and, by implication, continued rapid technical advance in these products.

Table 1
U.S. Smartphone Characteristics, IDC Data
Average characteristics by year

	2010	2011	2012	2013	2014	2015	2016	2017	Annual Average growth rate (percent)
Processor speed (GHz)	1.0	1.1	1.2	1.4	1.5	1.6	1.7	1.9	9
Cores	1.0	1.2	1.7	2.3	2.7	3.4	4.3	5.2	23
Storage (GB)	7.2	12.9	15.4	16.6	21.5	30.7	36.3	55.9	29
RAM	0.23	0.34	0.44	0.98	1.31	1.61	2.03	2.34	33
Camera resolution (megapixels)	4.2	5.2	6.5	7.8	8.7	9.7	10.1	10.4	13
Screen diagonal (inches)	3.3	3.5	3.8	4.2	4.5	4.7	4.9	5.1	6
Smartphone share of mobile phone units sold (percent)	38	55	69	77	88	87	91	94	
Herfindahl Index of market concentration	0.16	0.26	0.35	0.35	0.36	0.39	0.41	0.44	

Source: IDC Mobile Phone Tracker database.
Note: The Herfindahl index measure of market concentration is the sum of the squared revenue shares by manufacturer in the U.S. consumer market for smartphones.

Table 2
Quality-Adjusted Price Indexes for Smartphones, IDC Data
(average of quarterly percent changes, annual rate)

	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2011-2013**	**2014-2017**	**2010Q1-2018Q1**
1. Average prices	3.0	1.6	0.4	-6.9	-0.4	-14.7	11.9	1.7	-2.6	-0.8
<u>Matched-model indexes</u>										
2. Unweighted (Jevons)	-14.2	-9.8	-21.9	-18.9	-26.7	-29.3	-21.1	-15.3	-24.0	-19.3
3. Weighted (Tornqvist)	-4.7	-9.1	-12.7	-11.9	-12.9	-12.5	-9.8	-8.9	-11.8	-10.0
<u>Hedonic indexes</u>										
4. Time invariant	-8.8	-16.6	-16.2	-18.5	-16.9	-28.6	-24.7	-13.9	-22.2	-19.6
5. Time-varying effects (adjacent quarter)	**-6.5**	**-11.1**	**-16.8**	**-16.9**	**-14.9**	**-24.8**	**-19.4**	**-11.4**	**-19.0**	**-15.5**
6. Manufacturer-specific	-13.4	-12.6	-13.3	-20.5	-16.4	-23.8	-16.5	-13.0	-19.3	-16.0
Memo:										
Feature phones	-8.0	-16.8	-17.3	-48.6	-31.3	-7.8	-0.9	-14.0	-22.2	-18.5
Overall mobile phones	-9.6	-14.9	-15.2	-28.0	-18.8	-22.5	-15.3	-13.2	-21.1	-16.6
Byrne/Corrado index	-7.5	-19.9	-26.4	-28.8	-25.1	-25.0	NA	-17.9	-26.3	-22.1

Note: All hedonic indexes are revenue-weighted and control for manufacturer, processor speed, storage, screen size, camera resolution, operating system version, generation of wireless mobile technology, and input type. The manufacturer-specific regression index is a Fisher chain-weighted aggregate of indexes for 6 major manufacturers and a residual category. We apply to the results in lines 4 and 5 the adjustment suggested by van Dalen and Bode (2004) for adjacent-period regressions to correct for bias introduced when going from the natural log of prices to price levels, which is based on the standard error of the estimated coefficient on the second-period dummy. Average growth rates for Byrne/Corrado index extend through 2016. For the 2011-2016 period, the average growth rate for the overall mobile phone price index developed in this paper is -18.2, roughly 4 percentage points slower than for the Byrne/Corrado index.

Table 3
Summary Statistics Across Regressions: Time-varying Specification Estimated with Revenue-weighted Observations

	Mean	**Minimum**
Observations	417	145
r-squared	0.92	0.88
Adjusted r-squared	0.91	0.85
	Number of Regressions Significant out of 32	**Average Coefficient**
Storage	31	0.12
Camera Resolution	31	0.36
Screen Size	25	1.04
Processor Speed	23	1.00
Introduction-quarter Dummy	19	-0.06
	Number of Regressions out of 32 with at Least One Significant Coefficient of Category Shown	**Average Number of Significant Coefficients of Category Shown (zeros excluded)**
Operating System Version	28	5.4
Manufacturer	30	6.7
Input Type	12	1.2
Mobile Generation	5	1.2

Notes:
Significance measured at the 10 percent level. Continuous variables (storage, camera resolution, screen size, and processor speed) are measured in natural log terms, so coefficients represent price elasticities.
All significant coefficients for storage, camera resolution, screen size, and processor speed are positive. 14 of 19 significant coefficients for the entry-quarter dummy are positive.
Input types include QWERTY keyboard, touchscreen, and the combination of both. Mobile generations are commonly referred to as "2G", "3G", and so on and represent significant advances in the efficiency of data transmission on the associated network.

Table 4
Accounting for Service Providers' Equipment Revenues: Four examples

Scenario	Annual Reports*		SAS survey		Economic Census and PCE		Proposed PCE***	
	equipment	service	equipment	service	equipment	Services	equipment	services
---Phone purchase from wireless provider---								
1. $199 subsidized phone; $62.50 monthly service charge over 2-year contract	$199	$62.50/mo	$199	$62.50/mo	0	$199;$62.50/mo	$499	$50/mo
2. $499 phone with full payment up front; $50 monthly service charge	$499	$50/mo	$499	$50/mo	0	$499; $50/mo	$499	$50/mo
3. $499 phone with payment in installments; $50 monthly service charge	$499	$50/mo	$499	$50/mo	0	$499; $50/mo	$499	$50/mo
---Phone purchase at retail outlet---								
4. $499 phone upfront; $50 monthly service charge	n.a.	$50/mo	$499	$50/mo	$499	$50/mo	$499	$50/mo

*These are reported in the Income Statements, as equipment revenue and service revenue
**reported in SAS as "Reselling services for telecomm equipment, retail," Table 4 Sources of Revenue
***equipment category is Telephone and facsimile equipment; service category is recorded in Cellular Telephone Services

Table 5 **Allocation of PCE for Wireless Services Between Services and Devices**												
			2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**		**2010-2017**
	Personal Consumption Expenditures											
(1)	Cellular Telephone Service	Bill $	$98.0	$105.1	$107.0	$110.6	$119.4	$120.7	$124.5	$127.6		114.1
	Service Annual Survey (SAS)											
(2)	Total revenues	Bill $	199.2	214.4	225.4	233.1	251.8	254.4	259.3	257.8		236.9
(3)	Reselling services for telecomm equipment, retail	Bill $	18.8	21.0	23.7	24.7	35.5	41.3	44.4	46.7		32.0
(4) = (3)/(2)	Share of total revenues	percent	9.4	9.8	10.5	10.6	14.1	16.2	17.1	18.1		13.2
	IDC and JDPOWER average prices											
(5)	Ratio of average prices: IDC/JDPOWER	ratio	2.79	3.27	3.48	2.93	2.16	1.59	1.21	1.16		2.3
(6) = (5)x(4)	**Adjusted share of reselling services to total revenues**	percent	26.2	32.1	36.6	31.0	30.5	25.7	20.8	20.9		28.0
	Imputed detail for PCE for Cellular Telephone Services											
(7)=(1)x(6)	Phones	Bill $	25.7	33.7	39.1	34.3	36.4	31.0	25.9	26.7		31.6
(8)=(1) - (6)	Wireless Services	Bill $	72.3	71.4	67.9	76.3	83.0	89.6	98.7	100.9		82.5

Table 6
Average Prices ($), U.S. Smartphones

													Annual Average Growth Rate (percent)	
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**		**2007-2017**	**2010-2017**
IDC data	485	485	499	485	500	508	510	476	474	409	460		-0.5%	-0.8%
J.D. Power data	ND	ND	ND	174	153	146	174	220	299	337	398		ND	15.6%
excluding zero-price phones	ND	ND	ND	174	173	175	203	252	359	393	457		ND	15.5%

Table 7
Price Deflators and Real PCE for Cellular Telephone Services

	2010	2011	2012	2013	2014	2015	2016	2017	2010-2017
Components									
Estimated expenditure shares									
1. Phone	0.26	0.32	0.37	0.31	0.30	0.26	0.21	0.21	0.28
2. Services	0.74	0.68	0.63	0.69	0.70	0.74	0.79	0.79	0.72
Proposed deflators (percent change)									
3. Mobile Phones (this paper)		-9.6	-14.9	-15.2	-28.0	-18.8	-22.5	-15.3	-16.6*
4. Services (CPI Wireless Services)		-3.7	-0.8	-1.8	-2.2	-3.8	-1.0	-11.4	-3.5
Cellular Telephone Services (percent change)									
5. Prices: Tornquist aggregate of components on lines 3 and 4 using shares on lines 1 and 2		-5.4	-5.6	-6.3	-10.1	-8.0	-6.0	-12.2	-7.7
6. Nominal Spending		7.0	1.8	3.3	7.7	1.0	3.2	2.4	3.8
Real PCE Spending									
7. Proposed		12.4	7.4	9.7	17.8	9.1	9.2	14.6	11.4
8. Current		10.7	2.6	5.1	9.8	4.8	4.2	13.8	7.3
9. Difference		1.7	4.8	4.5	8.0	4.2	5.0	0.8	4.2

*Growth rate is from 2010Q1 to 2018Q1.

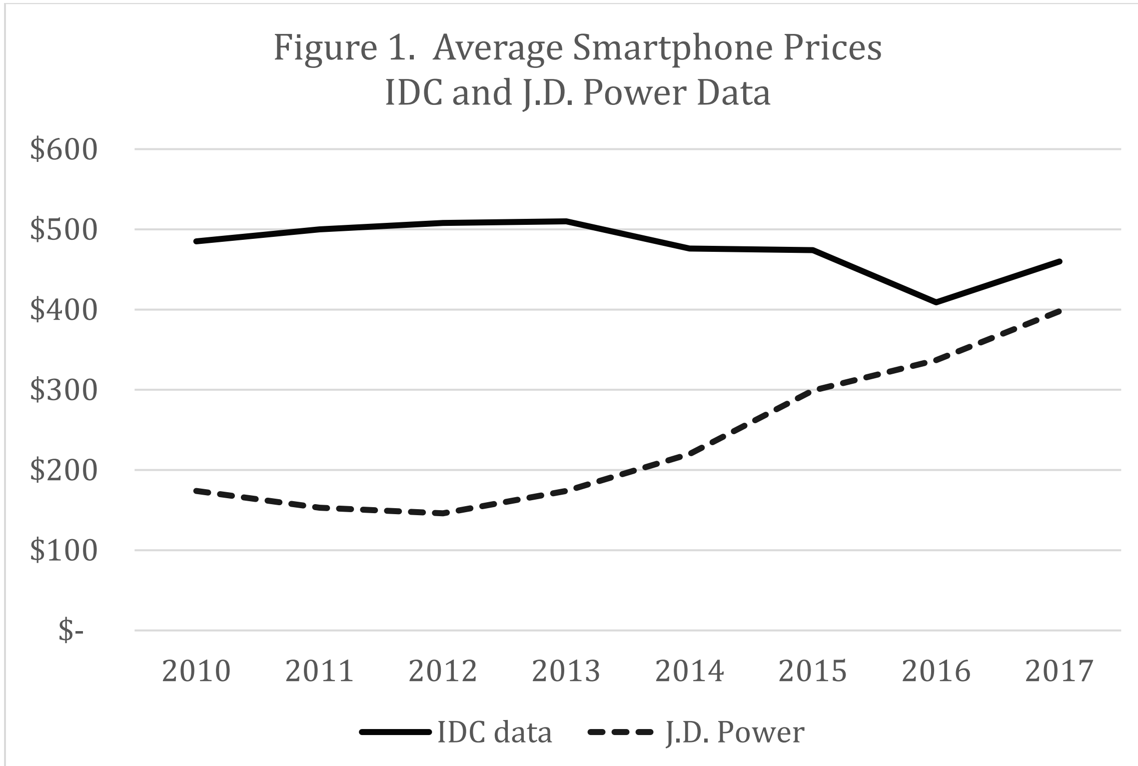
Figure 1. Average Smartphone Prices
IDC and J.D. Power Data
$600
$500
$400
$300
$200
$100
$-
2010
2011
2012
2013
2014
2015
2016
2017
IDC data
J.D. Power

Appendix

Table A1
Selected Adjacent-Quarter Regressions

	2010Q1 - 2010Q2			**2017Q4 - 2018Q1**		
Variable	**Coefficient**	**Std. Error**	**T Statistic**	**Coefficient**	**Std. Error**	**T Statistic**
Constant	6.886***	(1.417)	4.860	-14.21***	(5.298)	-2.681
Second Quarter	-0.123***	(0.0432)	-2.842	-0.00347	(0.0116)	-0.300
Performance Variables						
Storage	0.0464***	(0.0150)	3.094	0.145***	(0.00805)	17.97
Camera Resolution	0.528***	(0.0695)	7.605	0.367***	(0.0507)	7.226
Processor Speed	-0.209	(0.218)	-0.962	2.101***	(0.0755)	27.84
Screen Size	-0.0978	(0.199)	-0.492	1.360***	(0.0713)	19.08
Manufacturer						
Manufacturer # 5				0.450	(5.279)	0.0852
Manufacturer # 6				0.136	(0.198)	0.685
Manufacturer # 7	-0.0791	(0.0688)	-1.150	-0.239	(0.694)	-0.344
Manufacturer # 8				-0.249	(0.166)	-1.501
Manufacturer # 9				-0.189	(1.717)	-0.110
Manufacturer # 11				-0.187	(0.214)	-0.873
Manufacturer # 12	-0.416*	(0.234)	-1.782			
Manufacturer # 14				0.238	(0.187)	1.274
Manufacturer # 15	-0.462	(0.475)	-0.972	0.927	(1.709)	0.542
Manufacturer # 16	-0.255**	(0.0984)	-2.586	0.209	(0.196)	1.067
Manufacturer # 17	-0.333*	(0.176)	-1.896	-0.598***	(0.227)	-2.633
Manufacturer # 18				0.867***	(0.159)	5.449
Manufacturer # 19	-0.277**	(0.123)	-2.247	0.202	(0.142)	1.423
Manufacturer # 23	-0.684***	(0.0861)	-7.941	0.294**	(0.143)	2.048
Manufacturer # 25	-0.352	(2.028)	-0.174			

Table A1 continued
Example Adjacent Quarter Regressions

	2010Q1 - 2010Q2			2017Q4 - 2018Q1		
Variable	**Coefficient**	**Std. Error**	**T Statistic**	**Coefficient**	**Std. Error**	**T Statistic**
Manufacturer # 28	0.00463	(0.335)	0.0138			
Manufacturer # 30				0.204	(0.270)	0.756
Manufacturer # 31				0.196	(0.385)	0.508
Manufacturer # 33	-0.347***	(0.0790)	-4.388	0.360**	(0.143)	2.522
Manufacturer # 36				-0.176	(0.202)	-0.873
Manufacturer # 37	-0.251	(0.271)	-0.929			
Manufacturer # 39				-0.144	(0.152)	-0.946
Manufacturer # 40	-0.324***	(0.0879)	-3.685			
Manufacturer # 43				-0.155	(0.146)	-1.063
Operating Systems						
OS Version # 2	0.297***	(0.108)	2.735			
OS Version # 3	0.366***	(0.0559)	6.545			
OS Version # 4	-0.0648	(0.0678)	-0.955			
OS Version # 11				0.255	(5.283)	0.0482
OS Version # 14				-0.182	(5.277)	-0.0345
OS Version # 15				-0.293	(5.277)	-0.0555
OS Version # 16				-0.162	(5.277)	-0.0307
OS Version # 17				-0.225	(5.277)	-0.0427
OS Version # 18				-0.00140	(5.331)	-0.000262
OS Version # 21	0.198**	(0.0966)	2.050			
OS Version # 22	0.238***	(0.0473)	5.040			
OS Version # 23	0.121**	(0.0531)	2.273			
OS Version # 24	0.0938**	(0.0363)	2.582			

Table A1 continued
Example Adjacent Quarter Regressions

	2010Q1 - 2010Q2			2017Q4 - 2018Q1		
Variable	**Coefficient**	**Std. Error**	**T Statistic**	**Coefficient**	**Std. Error**	
OS Version # 29	-0.178	(2.135)	-0.0832			
OS Version # 30	0.162	(0.391)	0.415			
OS Version # 31	0.353	(0.540)	0.654			
OS Version # 32	-0.186	(2.034)	-0.0915			
OS Version # 33	-0.270	(2.029)	-0.133			
OS Version # 34	-0.361	(2.025)	-0.178			
OS Version # 38				-0.788	(5.429)	-0.145
OS Version # 39	0.214	(1.974)	0.108			
OS Version # 40	0.0213	(0.0725)	0.293			
OS Version # 41	-0.0381	(0.0705)	-0.540			
OS Version # 46				-0.274***	(0.0464)	-5.902
OS Version # 47				-0.124***	(0.0392)	-3.153
OS Version # 48	0.123	(0.0902)	1.363			
OS Version # 49	0.145*	(0.0738)	1.960			
OS Version # 56	-0.363	(0.329)	-1.103			
Telecommunications Generation						
2.5G	-0.333***	(0.110)	-3.037			
3G	-0.0740	(0.107)	-0.690			
4G	-0.0982	(0.150)	-0.653	0.137	(0.221)	0.619
Input Method						
QWERTY	0.0805	(0.460)	0.175			
QWERTY and Touchscreen	0.307	(0.468)	0.656			
Touchscreen	0.122	(0.467)	0.260	-0.791***	(0.141)	-5.624
Entry Quarter	-0.0939**	(0.0440)	-2.135	0.0693***	(0.0149)	4.637

Table A2
Preferred Quarterly and Annual Mobile Phone Price Indexes Based on IDC Data

	All Mobile Phones	Smartphones	Feature Phones
2010 Q1	4.68	4.73	4.32
2010 Q2	4.64	4.65	4.28
2010 Q3	4.57	4.57	4.22
2010 Q4	4.56	4.56	4.21
2011 Q1	4.54	4.56	4.18
2011 Q2	4.54	4.53	4.20
2011 Q3	4.52	4.50	4.19
2011 Q4	4.46	4.39	4.15
2012 Q1	4.39	4.38	4.05
2012 Q2	4.38	4.38	4.03
2012 Q3	4.37	4.38	4.01
2012 Q4	4.33	4.35	3.95
2013 Q1	4.32	4.34	3.95
2013 Q2	4.27	4.28	3.92
2013 Q3	4.17	4.21	3.77
2013 Q4	4.10	4.13	3.71
2014 Q1	4.02	4.11	3.48
2014 Q2	3.96	4.05	3.39
2014 Q3	3.92	4.01	3.36
2014 Q4	3.84	3.96	3.18
2015 Q1	3.84	3.95	3.17
2015 Q2	3.78	3.91	3.04
2015 Q3	3.73	3.85	2.99
2015 Q4	3.64	3.76	2.96
2016 Q1	3.60	3.72	2.91
2016 Q2	3.54	3.66	2.92
2016 Q3	3.51	3.61	3.00
2016 Q4	3.44	3.54	3.01
2017 Q1	3.42	3.52	2.99
2017 Q2	3.38	3.48	2.96
2017 Q3	3.32	3.42	2.92
2017 Q4	3.36	3.45	2.93
2018 Q1	3.35	3.45	2.84
2010	4.61	4.61	4.61
2011	4.51	4.47	4.52
2012	4.36	4.35	4.36
2013	4.21	4.21	4.18
2014	3.93	4.01	3.70
2015	3.74	3.84	3.38
2016	3.52	3.61	3.31
2017	3.36	3.44	3.30

References

Ahmadnejad, Moshen How many transistors were on the first iPhones processor. Available from https://www.quora.com/How-many-transistors-were-on-the-first-iPhones-processor [cited December 20, 2019 2018].

Aizcorbe, Ana (2014). *A Practical Guide to Price Index and Hedonic Techniques.* New York, NY: Oxford University Press.

Aizcorbe, Ana, Benjamin Bridgman, and Jeremy Nalewaik (2010). "Heterogeneous car buyers: A stylized fact," *Economics Letters,* vol. 109 (1), pp. 50-3.

Berndt, Ernst R. (1991). *The practice of econometrics: Classic and contemporary.* Reading, Mass.; Tokyo; Wokingham, U.K. and Sydney:; Addison-Wesley.

Bureau of Labor Statistics Measuring price change in the CPI: Telephone hardware, calculators, and other consumer information items. Bureau of Labor StatisticsAvailable from https://www.bls.gov/cpi/factsheets/telephone-hardware.htm [cited February 19, 2019 2019].

Byrne, David M., and Carol A. Corrado (2017). "ICT Asset prices: marshaling evidence into new measures," *Finance and Economics Discussion Series,* vol. 2017-016 .

———. (2015). "Prices for communications equipment: Rewriting the record," *Finance and Economics Discussion Series,* vol. 2015-069 .

Byrne, David M., John G. Fernald, and Marshall B. Reinsdorf (2016). "Does the United States have a productivity slowdown or a measurement problem?" *Brookings Papers on Economic Activity,* vol. 2016 (1), pp. 109-82.

Byrne, David M., Stephen D. Oliner, and Daniel E. Sichel (2017). "How fast are semiconductor prices falling?" *Review of Income and Wealth,* .

Byrne, David, Stephen Oliner, and Daniel Sichel (2017). "Prices of high-tech products, mismeasurement, and the pace of innovation," *Business Economics,* vol. 52 (2), pp. 103-13.

Chessa, Antonio G. (2016). Processing scanner data in the dutch CPI: A new methodology and first experiences. Paper presented at Meeting of the Group of Experts on Consumer Price Indices, .

Cole, Rosanne, Y. C. Chen, Joan Barquin-Stolleman, Ellen Dulberger, Nurhan Halvacian, and James Hodge (1986). "Quality-adjusted Price Indexes for Computer Processors and Selected Peripheral Equipment," *Survey of Current Business*, vol. 66 (1), pp. 41-50.

Diewert, W. E. (1998). "Index Number Issues in the Consumer Price Index," *Journal of Economic Perspectives*, vol. 12 (1), pp. 47-58.

———. (1976). "Exact and superlative index numbers," *Journal of Econometrics*, vol. 4 (2), pp. 115-45.

Guvenen, Fatih, Raymond J. Mataloni Jr, Dylan G. Rassier, and Kim J. Ruhl (2017). *Offshore profit shifting and domestic productivity measurement*, .

Guvenen, Fatih, Raymond Mataloni, Dylan Rassier, and Kim Ruhl (2016), "Offshore Profit Shifting and Domestic Productivity Measurement," .

Hennessy, John, and David Patterson (2011). *Computer architecture: a quantitative approach.* Elsevier.

International Data Corporation (2018). "IDC's Worldwide Mobile Phone Tracker Taxonomy, 2018," Documentation, .

Karamti, Chiraz, and Nejib Haouech "Introducing hedonic quality adjustment in the official price statistics: Evidence from the Tunisian smartphones market," .

Pakes, Ariel (2003). "A Reconsideration of Hedonic Price Indexes with an Application to PC's," *American Economic Review*, vol. 93 (5), pp. 1578-96.

Pashigian, B. P., Brian Bowen, and Eric Gould (1995). "Fashion, Styling, and the Within-Season Decline in Automobile Prices," *Journal of Law and Economics*, vol. 38 (2), pp. 281-309.

Shankland, Steven iPhone XS A12 bionic chip is industry-first 7nm CPU. CNETAvailable from https://www.cnet.com/news/iphone-xs-a12-bionic-chip-is-industry-first-7nm-cpu/ [cited February 19, 2019 2019].

Triplett, Jack (2006). *Handbook on Hedonic Indexes and Quality Adjustments in Price Indexes: Special Application to Information Technology Products.* Paris and Washington, D.C.: Organisation for Economic Co-operation and Development.

van Dalen, Jan, and Ben Bode (2004). Estimation biases in quality-adjusted hedonic price indices. Paper presented at SSHRC International Conference on Index Number Theory and the Measurement of Prices and Productivity, Vancouver, June, .

Watanabe, Naoki, Ryo Nakajima, and Takanori Ida (2010). "Quality-Adjusted Prices of Japanese Mobile Phone Handsets and Carriers' Strategies," *Review of Industrial Organization*, vol. 36 (4), pp. 391-412.

Williams,Brendan and Erick Sanger (2018). "A New Vehicles Transaction Price Index: Offsetting the Effects of Price Discrimination and Product Cycle Bias with a Year-Over-Year Index," Meeting of the Group of Experts on Consumer Price Indexes Geneva, Switzerland, May 7-9, 2018, May 7, 2018.