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Hedonic Prices for Multicomponent Products

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The price of a smartphone likely reflects its functional features that consumers value, such as its storage capacity, camera resolution, battery life, display size, and display resolution, among others. However, a nontrivial portion of the price of a smartphone might also be attributable to the brand name and its perceived social value, rather than the smartphone's functionality. For example, in *TCL v. Ericsson*, a TCL witness testified that Samsung's brand name alone contributes more than $300 of the value to a Samsung smartphone.[1] As of December 2018, that estimated brand value exceeded half of the median price of a Samsung phone available in the United States, and it exceeded one quarter of the price of Samsung's most expensive smartphone available in the United States.[2] In this article, we conduct an econometric analysis to test whether a smartphone's brand possesses statistically significant explanatory power for a smartphone's price above and beyond the functional features of a smartphone, and we find that it does.

Hedonic price analysis is an econometric methodology that enables one to isolate the value attributable to each component of a multicomponent product. By regressing a product's total price on the product's characteristics,

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1 Corrected Non-Confidential Brief for Appellants Ericsson Inc. & Telefonaktiebolaget LM Ericsson at 53, TCL Commc'n Tech. Holdings, Ltd. v. Telefonaktiebolaget LM Ericsson, No. 18-1363 (Fed. Cir. June 20, 2018), 2018 WL 3440544, at *53.

2 Among smartphones implementing the 4G LTE standard that are available for sale in the United States as of December 2018, the average price of a Samsung phone was $497.52, the median price of a Samsung phone was $540.00, and the price of the most expensive Samsung phone (the Samsung Galaxy S8+) was $1,099. STRATEGY ANALYTICS, SPECTRAX DATABASE (Dec. 2018).

hedonic price analysis enables one to determine how much consumers are willing to pay for individual components of a multicomponent product (such as a smartphone), including the product's brand. In this article, we conduct hedonic price analysis of smartphones available in the United States as of December 2018. To our knowledge, as of April 2019, this article is the first publicly reported hedonic price analysis of the demand for features of smartphones in the United States that uses an objective variable selection method based on a machine learning algorithm—the "least absolute shrinkage and selector operator" (LASSO) regression—to identify the functional features that are the best predictors of a smartphone's price. The existing empirical literature has relied on a set of explanatory variables that were chosen either arbitrarily or on the basis of heuristics used by marketing firms. Our hedonic price model tests the hypothesis that a smartphone's brand possesses statistically significant explanatory power for a smartphone's price above and beyond the smartphone's functional features. To the extent that this methodology is used in litigation or arbitration, one advantage of this approach is that it does not rely on any confidential business information, which in turn contributes to its replicability.

In Part I, we explain that economists routinely use hedonic price analysis to explain a good's price in terms of its characteristics, and that a nascent economic literature exists on the use of hedonic price models to estimate the implicit price associated with each of a smartphone's components. In Part II, we use an objective econometric methodology that applies a machine learning algorithm to select a set of functional features of a smartphone that best explain a smartphone's price. On the basis of our objectively selected features, we develop a hedonic price model to derive the value attributable to various features of a smartphone, including its brand. The results of our hedonic price analysis suggest that a smartphone's brand can possess statistically significant explanatory power above and beyond the smartphone's functional features. In Part III, we test the robustness of our results by analyzing alternative forms of our hedonic price model. We find that the results of our hedonic price analysis—that a smartphone's brand possesses statistically significant explanatory power for a smartphone's price—are robust to various alternative specifications of the model.

I. The Economic Literature on Hedonic Prices for the Components of a Smartphone

In his 1966 article on the theory of consumption, Kelvin Lancaster specified that a good generally possesses multiple characteristics, and that consumers derive utility from the individual characteristics that comprise a good.[3] Applying that theory of consumption, Sherwin Rosen said in his 1974 article that "[o]bserved product prices and the specific amounts of characteristics associated with each good define a set of implicit or 'hedonic' prices."[4] In other words, the observed market price of a good reflects the sum of the prices of the good's constituent characteristics, and one can use a hedonic price model to explain a good's price in terms of the good's characteristics.[5]

Under the theory of hedonic prices, one can determine how much consumers are willing to pay for each component of a product by regressing the product's total price on the product's characteristics.[6] The implicit price of each of the product's characteristics—how much the consumer reveals that she would be willing to pay for that characteristic and therefore the minimum amount that the consumer values that characteristic—is statistically determined from observed prices, features, and sales quantities in the market.[7] The best candidates for hedonic price analysis are goods for which changes in the components are frequent, observable, measurable, and relatively easy to identify and quantify.[8] Economists have conducted hedonic price analysis to estimate a good's quality-adjusted price index or to estimate the implicit prices of a good's characteristics, in the context of goods ranging from houses[9] and automobiles[10] to high-technology products including PCs,[11]

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[3] Kelvin J. Lancaster, *A New Approach to Consumer Theory*, 74 J. Pol. Econ. 132, 133–34 (1966).

[4] Sherwin Rosen, *Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition*, 82 J. Pol. Econ. 34, 34 (1974).

[5] Ariel Pakes, *A Reconsideration of Hedonic Price Indexes with an Application to PC's*, 93 Am. Econ. Rev. 1578, 1580 (2003).

[6] *See id.*

[7] *See* Mary Kokoski, Keith Waehrer & Patricia Rozaklis, *Using Hedonic Methods for Quality Adjustment in the CPI: The Consumer Audio Products Component* 3 (Bureau of Labor Stat., Working Paper No. 344, Mar. 2001).

[8] *See id.*

[9] *See, e.g.*, Ann D. Witte, Howard J. Sumka & Homer Erekson, *An Estimate of a Structural Hedonic Price Model of the Housing Market: An Application of Rosen's Theory of Implicit Markets*, 47 Econometrica 1151 (1979).

[10] *See, e.g.*, G. Baltas & C. Saridakis, *Measuring Brand Equity in the Car Market: A Hedonic Price Analysis*, 61 J. Operational Res. Soc'y 284 (2010); Fiona Scott Morton, Jorge Silva-Risso & Florian Zettelmeyer, *What Matters in a Price Negotiation: Evidence from the U.S. Auto Retailing Industry*, 9 Quantitative Marketing & Econ. 365, 384 (2011).

[11] *See, e.g.*, Pakes, *supra* note 5; Adrian Ball & Andrew Allen, *The Introduction of Hedonic Regression Techniques for the Quality Adjustment of Computing Equipment in the Producer Prices Index (PPI) and Harmonised Index of Consumer Prices (HICP)* (Off. of Nat'l Stat., Econ. Trends No. 592, Feb. 10, 2003), http://www.statistics.gov.uk/articles/economic_trends/PC_Hedonics_Regression.pdf.

personal digital assistants,[12] mobile phones,[13] stereo receivers,[14] and memory modules for enterprise servers.[15]

More recent studies have applied the theory of hedonic prices in the context of smartphones. Whereas most of those studies have applied hedonic price models to develop quality-adjusted price indices for smartphones,[16] some have used hedonic price models to estimate the implicit price associated with each of a smartphone's components. Here, we provide an overview of the latter category of studies and explain how this article advances that existing economic literature.[17]

A. Montenegro and Torres (2016)

In their 2016 working paper, José Montenegro and José Torres use a hedonic price model to estimate the implicit prices associated with a smartphone's characteristics.[18] They analyze the price and certain technical features of

12 *See, e.g.*, Paul D. Chwelos, Ernst R. Berndt & Iain M. Cockburn, *Faster, Smaller, Cheaper: An Hedonic Price Analysis of PDAs* (NBER Working Paper No. 10746, Sept. 2004).

13 *See, e.g.*, Ralph Dewenter, Justus Haucap, Ricardo Luther & Peter Rötzel, *Hedonic Prices in the German Market for Mobile Phones*, 31 Telecomm. Pol'y 4 (2007).

14 *See, e.g.*, Teague Ruder & Ted To, Brand Dummy Variables in Hedonic Regressions: A Study Using Stereo Receiver Scanner Data (Jan. 2004) (unpublished manuscript), http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.202.7429&rep=rep1&type=pdf.

15 In a 2017 article, we performed hedonic price analysis on the prices of load-reduced dual-inline memory modules (LRDIMMs) to estimate the permissible range for a reasonable royalty for a standard-essential patent (SEP) subject to its owner's commitment to offer to license the patent on reasonable and nondiscriminatory (RAND) terms. J. Gregory Sidak & Jeremy O. Skog, *Hedonic Prices and Patent Royalties*, 2 Criterion J. on Innovation 601 (2017). For a commentary on our analysis, see Alexander Galetovic, *Hedonic Prices, Patent Royalties, and the Theory of Value and Distribution: A Comment on Sidak and Skog*, 3 Criterion J. on Innovation 59 (2018).

16 *See, e.g.*, Ivan Forenbacher, Dragan Peraković & Siniša Husnjak, *Hedonic Modeling to Explore the Relationship of Cell Phone Plan Price and Quality in Croatia*, 33 Telematics & Informatics 1057 (2016); Seong Hun Yun, Yongjae Kim & Minki Kim, *Quality-Adjusted International Price Comparisons of Mobile Telecommunications Services*, 43 Telecomm. Pol'y 339 (2019); David M. Byrne, Daniel E. Sichel & Ana Aizcorbe, *Getting Smart About Phones: New Price Indexes and the Allocation of Spending Between Devices and Services Plans in Personal Consumption Expenditures* (Federal Reserve Board, Finance and Economics Discussion Series No. 2019-012, 2019), https://doi.org/10.17016/FEDS.2019.012; Qiwei Han & Daegon Cho, Characterizing the Technological Evolution of Smartphones: Insights from Performance Benchmarks, Proceedings of the 18th Annual International Conference on Electronic Commerce: e-Commerce in Smart Connected World, Article No. 32 (Aug. 2016), https://dl.acm.org/citation.cfm?id=2971635; Wook Joon Kim & Yongkyu Kim, An Estimation of Quality-Adjusted Prices for Mobile Services in Korea, The 22nd Biennial Conference of the International Telecommunications Society: "Beyond the Boundaries: Challenges for Business, Policy and Society" (June 15, 2018), https://www.econstor.eu/handle/10419/190346.

17 At least one study examines a fundamentally different question from the one that we examine. In their 2016 article Yuri Park and Yoonmo Koo perform a conjoint analysis on customer survey data to analyze the costs that South Korean consumers face (1) when switching from the use of one smartphone device to another and (2) when switching from the use of one operating system to another. Yuri Park & Yoonmo Koo, *An Empirical Analysis of Switching Cost in the Smartphone Market in South Korea*, 40 Telecomm. Pol'y 307 (2016). Unlike a conjoint analysis that relies on customer survey data, a hedonic price analysis uses observed market price data to examine the revealed preferences of consumers. Here, we focus on providing an overview of studies that use market data rather than consumer survey data.

18 José A. Montenegro & José L. Torres, *Consumer Preferences and Implicit Prices of Smartphone Characteristics* (Málaga Economic Theory Research Center Working Paper No. 2016-4, Nov. 2016).

312 observations of handsets that were introduced to the market in 2012.[19] Montenegro and Torres find that the two smartphone characteristics that consumers value most are (1) screen resolution and (2) screen size, and they find that other characteristics that consumers value include a smartphone's memory, the number of CPUs, and battery capacity.[20] In contrast, they find that consumers do *not* value a smartphone's camera resolution, the availability of a secondary camera, the graphics processing unit (GPU), or the near-field communication (NFC) feature.[21]

Montenegro and Torres find that a smartphone's weight has a statistically significant positive relationship with its price.[22] However, they explain that that result does not indicate that consumers prefer heavier smartphones.[23] Rather, they conclude that positive relationship might result because a higher-priced smartphone is more likely than a lower-priced smartphone to contain (1) a higher-capacity battery, (2) a larger screen size, and (3) higher-quality casing and screen materials (such as metal, steel, and tempered glass, as opposed to plastic), all of which increase a smartphone's weight.[24]

Montenegro and Torres also find that certain brands of smartphones command a premium. Specifically, they find that "consumers are willing to pay up to a 95% premium for an Apple smartphone."[25] (However, it bears emphasis that their estimation sample includes only one observation of an Apple smartphone.[26]) Although Montenegro and Torres also examine whether different operating systems are associated with an "OS premium," they caution that "a potential OS premium cannot be disentangled from a brand premium," because the operating system of a phone in some cases (for example, iOS) is brand-specific.[27] In other words, Montenegro and Torres conclude that it is impossible, with their data, to identify the value of the operating system separately from the value of the brand.

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[19] *Id.* at 5. Montenegro and Torres analyze seven categories of a smartphone's features: (1) design, (2) cameras, (3) display, (4) communication, (5) performance, (6) operating systems, and (7) connectivity. *Id.* at 7.

[20] *Id.* at 3. Montenegro and Torres note that, because smartphones enable many applications other than phone calls, the most appropriate measure of battery capacity for a smartphone has changed from a measure of talk time in older generations of mobile phones to a measure of battery power in newer generations of mobile phones. Thus, they use milli-Ampere hours (mAh), as opposed to talk time or standby time, to measure the battery capacity of a smartphone. *Id.* at 9.

[21] *Id.* at 3.

[22] *Id.* at 14.

[23] *Id.*

[24] *Id.*

[25] *Id.* at 17.

[26] *See id.* at 6 (showing that 0.3 percent of all smartphones in the authors' database use the iOS operating system, which is equal to one handset—that is, 312 × 0.3%).

[27] *Id.* at 17.

B. Ahmad, Ahmed, and Ahmad (2019)

In their 2019 article, Waseem Ahmad, Tanvir Ahmed, and Bashir Ahmad use a hedonic price model for smartphones sold in Pakistan to estimate the effect that different features of a smartphone have on the smartphone's retail price.[28] Their hedonic price analysis uses price data from November 2016 to February 2017,[29] and their estimation sample includes 348 smartphone models.[30] Ahmad, Ahmed, and Ahmad include in their hedonic price model indicator variables for (1) types of smartphone brands, (2) levels of weight, (3) levels of battery capacity (measured in mAh), (4) types of operating systems, (5) levels of RAM, (6) levels of storage capacity, (7) levels of display size, (8) generation of the mobile network compatible with the device, (9) levels of rear camera resolution, (10) the availability of a front camera, and (11) the availability of FM radio.[31]

Ahmad, Ahmed, and Ahmad find that a smartphone's battery capacity, weight, RAM, memory size, display size, rear camera resolution, availability of a front camera, and availability of FM radio are features that have a statistically significant positive effect on the smartphone's price.[32] They also find, as Montenegro and Torres do, that a smartphone's weight has a statistically significant positive effect on a smartphone's price.[33] Unlike Montenegro and Torres, however, Ahmad, Ahmed, and Ahmad explain that "there is no significant correlation between weight and [battery capacity or screen size] as indicated by the correlation coefficient values."[34]

With respect to brand, Ahmad, Ahmed, and Ahmad find that the "iPhone is ranked as a top brand with a 240.42 percent premium price in the market," relative to the "other" brand category (which includes brands that offer fewer than 20 models of smartphones in the authors' dataset).[35] Other brands that Ahmad, Ahmed, and Ahmad find command a premium relative to the "other" brand category include Rivo (65.97 percent), Samsung (32.36 percent), Haier (30.05 percent), and Huawei (22.66 percent).[36]

Ahmad, Ahmed, and Ahmad also analyze a smartphone's operating system and find that, "[o]ther things being equal, the Android system price was significantly higher while the [i]OS operating system showed a non-significant impact on price with reference to the base category,

[28] Waseem Ahmad, Tanvir Ahmed & Bashir Ahmad, *Pricing of Mobile Phone Attributes at the Retail Level in a Developing Country: Hedonic Analysis*, 43 Telecomm. Pol'y 299 (2019).
[29] *Id.* at 299.
[30] *Id.* at 305.
[31] *Id.* at 304.
[32] *Id.* at 306.
[33] *Id.*
[34] *Id.* at 305.
[35] *Id.*
[36] *Id.*

Symbian."[37] In other words, they find that consumers in Pakistan derive a higher value from the Android operating system than they do from iOS or the Symbian operating system. They explain that that result might be due to two factors: (1) Android, unlike iOS, is an open-source operating system that enables users to download and install third-party applications and (2) more applications are available on the Android operating system than on the Symbian operating system.[38]

However, Ahmad, Ahmed, and Ahmad emphasize that "[o]ne major limitation of th[eir] study is its confinement to only one developing country, Pakistan."[39] They explain that the utility that consumers derive from various features of smartphones might differ across countries because of differences in socioeconomic factors.[40] Thus, the implications (if any) of the authors' findings for U.S. consumer demand for various smartphone features are not apparent.

C. Summation

In sum, the nascent economic literature on the hedonic price analysis of consumer demand for smartphone features has not focused on U.S. consumers specifically. To our knowledge, this article is the first publicly reported hedonic price analysis of U.S. consumer demand for smartphone features that seeks to estimate the value that consumers attribute to the brand of a smartphone above and beyond its functional features. Moreover, the hedonic price models in the existing literature contain independent variables for which the selection method is arbitrary or unclear. This article improves upon the existing literature by using an objective statistical optimization technique that applies a machine-learning algorithm to select the independent variables that are most predictive of a smartphone's price.

II. Estimating the Value Attributable to Various Smartphone Features

Customers differentiate smartphones on the basis of various features, which include storage capacity, camera resolution, battery life, display size, display resolution, and brand value, among others. To estimate the implicit price that consumers have demonstrated that they are willing to pay for various smartphone features, we first use an objective statistical methodology to select the functional features that best predict a smartphone's price. Then, we use a hedonic price model that includes those selected functional features

[37] *Id.* at 306–07.
[38] *Id.* at 307.
[39] *Id.* at 308.
[40] *Id.* at 300.

to test the hypothesis that a smartphone's brand possesses statistically significant explanatory power for a smartphone's price above and beyond a smartphone's functional features. We find that the regression results support the conclusion that at least some portion of the price that some consumers have demonstrated that they are willing to pay for a smartphone is attributable to factors unrelated to the smartphone's functionality, such as its brand.

A. Description of the Data

We use data retrieved in December 2018 from Strategy Analytics' SpecTRAX database, which tracks more than 300 features and technical specifications of mobile electronic devices including smartphones, feature phones, tablets, and wearables sold worldwide.[41] We limit our analysis to smartphones implementing the 4G LTE standard that are available for sale in the United States as of December 2018.[42] We also exclude from our analysis smartphone models for which price data do not exist. Our narrowed dataset thus includes information on 370 feature variables (including price) for 711 smartphone models sold by 40 brands. In Appendix I, we describe each feature variable included in our dataset. We now proceed by providing some descriptive statistics for the data.

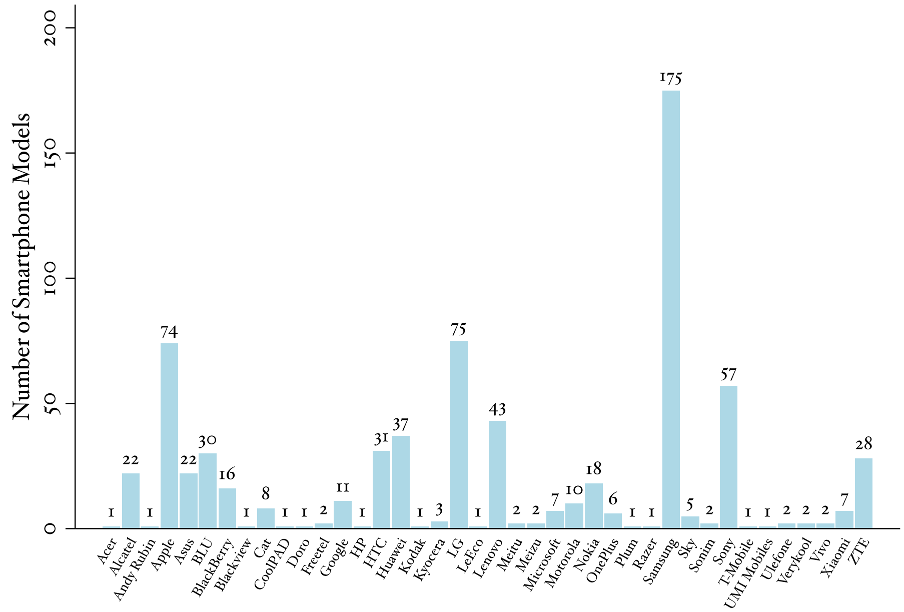
1. Number of Smartphone Models by Brand

Figure 1 reports the number of smartphone models available from each brand in our dataset.

[41] *About SpecTRAX*, Strategy Analytics, https://www.strategyanalytics.com/access-services/devices/mobile-phones/specifications-and-pricing/spectrax/about-spectrax.

[42] That is, the analysis includes only devices that indicate (1) "Active" under the "Current Status" column, (2) "Yes" under the "Cellular Connection" column, (3) "4G" under the "Network Generation" column, and (4) "Smartphone" under the "Product Type" column. Strategy Analytics, SpecTRAX Database, *supra* note 2, tab 2 ("Device Specifications").

Figure 1. Number of Smartphone Models by Brand



Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

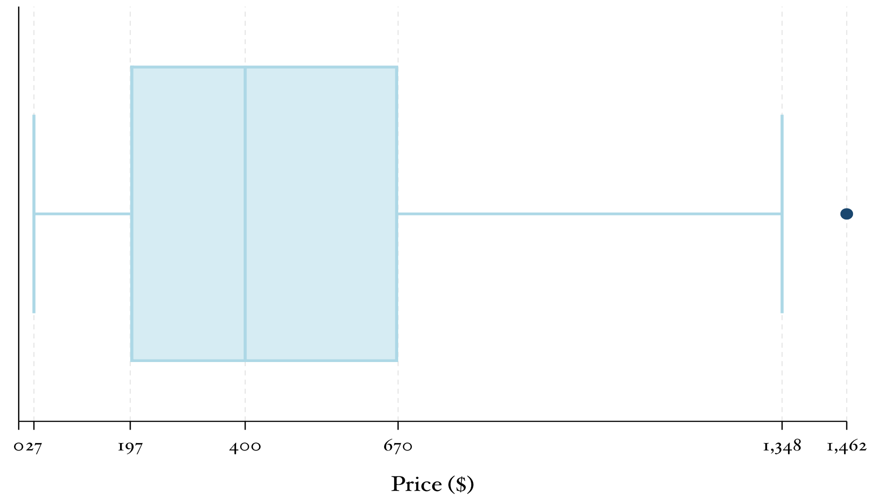
As Figure 1 shows, brands that offer the highest number of smartphone models in the United States include Samsung (175 models), LG (75 models), Apple (74 models), Sony (57 models), and Lenovo (43 models). Together, these five brands account for 59.6 percent of all smartphone models available in our dataset.[43] To analyze whether the high concentration of smartphone models across a few brands affects the results of our hedonic price model, in Part III.B.4 we examine an alternative specification of the model that excludes brands that offer fewer than three smartphone models, and we conclude that our model is robust to the exclusion of those brands that sell fewer smartphone models.

2. *Distribution of Smartphone Prices*

Strategy Analytics' SpecTRAX database includes information on the price of each smartphone model as of December 2018, which Strategy Analytics defines as "[t]he recommended retail price (if given by the vendor) unsubsidized."[44] Figure 2 shows a boxplot distribution of prices for all smartphones in our dataset.

[43] That is, (175 + 75 + 74 + 57 + 43) ÷ 711 = 59.6%.
[44] Strategy Analytics, SpecTRAX Field Definitions for Criterion (Mar. 22, 2019). The price variable in the Strategy Analytics database reflects the "launch price," or the price of a smartphone model

Figure 2. Distribution of Smartphone Prices



Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

In Figure 2, the vertical line inside the box represents the median of the price distribution for all smartphones in our dataset ($400.00), the hinge on the left-hand side of the box represents the 25th percentile of the price distribution ($197.00), and the hinge on the right-hand side of the box represents the 75th percentile of the price distribution ($670.00).[45] The vertical line outside the box on the left-hand side represents the lower adjacent value of the distribution—that is, the lowest value in the distribution that exceeds the lower inner fence of the distribution, which equals Q25 – 1.5 × (Q75 – Q25).[46] In Figure 2, the lower inner fence of the distribution is –$512.50 (that is, $197.00 – 1.5 × ($670.00 – $197.00)). Because the lower inner fence is negative in this case, the lower adjacent value of the distribution is simply the minimum price, $27.00. Similarly, the vertical line outside the box on the right-hand side represents the upper adjacent value of the distribution—that is, the highest value in the distribution that falls below the upper inner fence of the distribution, which equals Q75 + 1.5 × (Q75 – Q25).[47]

at the time of its launch. We analyze whether limiting our hedonic price model to smartphone models that were launched recently (that is, in 2017 or 2018), rather than including all smartphone models that are currently available, changes the conclusion of our analysis, and we find that it does not. Appendix II reports the regression results of an alternative specification of our hedonic price model that is limited to smartphone models that were launched in 2017 or 2018. As Appendix II reports, we still observe that a smartphone's brand possesses statistically significant explanatory power for the smartphone's price unrelated to the smartphone's functional features.

45 *See* Michael N. Mitchell, A Visual Guide to Stata Graphics 227 (Stata Press 3d ed. 2012).

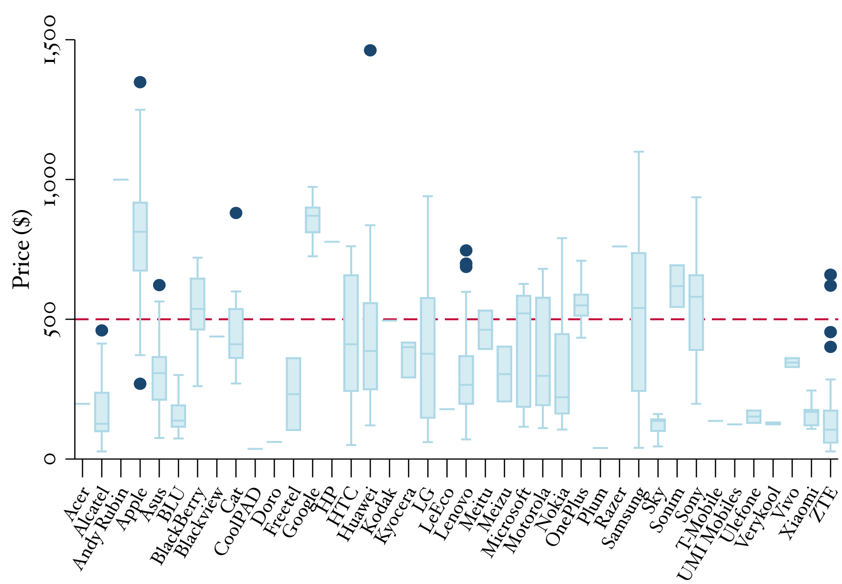
46 *See* R. Allan Reese, *Boxplots*, Significance, Sept. 2005, at 134, 134, https://rss.onlinelibrary.wiley.com/doi/epdf/10.1111/j.1740-9713.2005.00118.x.

47 *See id.*

In Figure 2, the upper inner fence of the distribution is $1,379.50 (that is, $670.00 + 1.5 × ($670.00 – $197.00)). The upper adjacent value of the distribution is $1,348.00, because it is the highest value in the distribution that falls below the upper inner fence. Finally, the dot in Figure 2 represents an outlier of the price distribution ($1,462.00), which is a value that lies outside the inner fences of the distribution.[48] There are no outliers on the left-hand side of the distribution in Figure 2 because all prices in our dataset are positive, and thus they all exceed the value of the lower inner fence (which is negative).

Figure 3 displays a box plot showing the distribution of smartphone prices by brand.

Figure 3. Distribution of Smartphone Prices by Brand



Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

As Figure 3 shows, of the 40 brands of smartphones available in our dataset, 11 brands have a median smartphone price that exceeds $500: Andy Rubin ($999.00), Apple ($812.50), BlackBerry ($537.00), Google ($870.00), HP ($777.00), Microsoft ($521.00), OnePlus ($548.87), Razer ($760.00), Samsung ($540.00), Sonim ($618.00), and Sony ($580.00). Some brands (such as Acer, Andy Rubin, Blackview, CoolPAD, Doro, and HP, among others) offer only one model of smartphone. For those brands, the distribution of prices is represented by a single blue dash. For brands that offer multiple smartphone models (such as Alcatel, Apple, HTC, Huawei, LG, Samsung, Sony, and ZTE,

[48] *See id.*

among others), the dash inside each box indicates the median of the price distribution for that particular brand, whereas the upper hinge of the box indicates the 75th percentile of the price distribution and the lower hinge of the box represents the 25th percentile of the price distribution for that particular brand.

Figure 4 displays a histogram showing the frequency of smartphone models by price range in $50 increments. Each bar displays the number of smartphone models that exist within that particular price range. For example, the first bar in Figure 4 indicates the number of smartphone models whose prices fall within the range of $0 to $49.99, and the second bar indicates the number of smartphone models whose prices fall within the range of $50.00 to $99.99. In Figure 4, we also overlay the histogram with a line representing the "smoothed" version of the histogram that shows the trend in the price distribution.

Figure 4. Histogram of Smartphone Prices

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

As Figure 4 shows, the distribution of prices appears to be bimodal—that is, there appear to be two distinct modes, or "peaks," in the distribution. One might argue that such a distribution indicates that a smartphone with a lower price point and a smartphone with a higher price point belong in two different market segments. In Part III.B.3, we analyze whether we obtain different results when we limit our analysis to smartphones with higher price points. Specifically, we examine whether our hedonic price model is robust to the alternative specification including only "ultra premium" smartphones with prices exceeding $500, and we find that it is.

B. *Selecting Explanatory Variables for a Smartphone's Price Using a LASSO Regression*

Although our dataset includes 372 variables for a smartphone's features, not all of those variables might explain a consumer's demonstrated willingness to pay for a smartphone.[49] For example, some features (such as display size) might possess greater explanatory power than others (such as the processor vendor, which typically is not directly observable to a consumer). Which of a smartphone's features best explain a smartphone's price? Typically, when searching for publicly available information on the most important features of a smartphone, one encounters surveys by market research firms whose data and methods are unclear, not replicable, or otherwise deficient owing to possible methodological errors or the criticism that the results are subjective.[50] Rather than rely on those surveys, we use an objective and replicable statistical methodology that applies a machine learning algorithm—the "least absolute shrinkage and selection operator" regression[51]—to select explanatory variables to include in our hedonic price model. Put differently, by selecting variables through the LASSO regression, we avoid relying on any idiosyncratic or arbitrary choice of variables.

An econometric model that includes too many predictor variables is susceptible to overfitting, which results when a model includes unnecessary variables that do not add explanatory power to the model.[52] An

[49] Because our hedonic price model uses actual price data, we cannot directly observe the consumer's theoretical *maximum* willingness to pay. Instead, we observe the consumer's *demonstrated* willingness to pay, which is less than or equal to her maximum willingness to pay. *See* Sidak & Skog, *Hedonic Prices and Patent Royalties*, *supra* note 15, at 660; J. Gregory Sidak, *Bargaining Power and Patent Damages*, 19 Stan. Tech. L. Rev. 1, 13 (2015).

[50] *See, e.g.*, Kantar Worldpanel, An Incredible Decade for the Smartphone: What's Next?: The Future of Mobile Is in Combining Devices, Content, and Services 4 (2017), https://www.kantarworldpanel.com/global/News/2017-smartphone-industry-insight-report; *Most Important Smartphone Properties According to U.S. Consumers 2017*, Statista, https://www.statista.com/statistics/716243/smartphone-properties-important-to-us-consumers/.

[51] *See* Robert Tibshirani, *Regression Shrinkage and Selection via the Lasso*, 58 J. Royal Stat. Soc'y 267 (1996); Sendhil Mullainathan & Jann Spiess, *Machine Learning: An Applied Econometric Approach*, 31 J. Econ. Persp. 87 (2017); Susan Athey, *The Impact of Machine Learning on Economics*, *in* The Economics of Artificial Intelligence: An Agenda (Univ. of Chicago Press forthcoming 2019); *Least Absolute Shrinkage and Selection Operator (LASSO)*, Columbia University Mailman School of Public Health, https://www.mailman.columbia.edu/research/population-health-methods/least-absolute-shrinkage-and-selection-operator-lasso.

[52] *See* Damodar N. Gujarati, Dawn C. Porter & Sangeetha Gunasekar, Basic Econometrics 495, 498 (McGraw Hill 5th ed. 2009); Jeffrey M. Woolridge, Introductory Econometrics: A Modern Approach 83–84 (Cengage Learning, Inc. 2020).

overfitted model produces estimates with high variance and low bias.[53] That is, the model might predict an existing set of data with high accuracy, but it might not accurately predict new data that one observes. In contrast, an econometric model that includes too few predictor variables is susceptible to underfitting, which results when a model omits relevant variables that add explanatory power to the model.[54] An underfitted model produces estimates with high bias and low variance.[55] That is, the model is likely to predict new data at least as accurately as it predicts the existing data that one uses to estimate the model, but neither prediction will provide a good estimate of the true relationship between the dependent variable and independent variables.

A LASSO regression mitigates the concern of underfitting or overfitting the model by minimizing the model's total mean squared error, which is "[t]he expected squared distance that an estimator is from the population value."[56] The LASSO regression is a form of "penalized regression" that selects variables by minimizing a loss function. In other words, it selects variables by penalizing standardized beta coefficients that have little statistical explanatory power and thereby reducing those coefficients to zero (which is equivalent to eliminating the variable from the model).[57] The LASSO regression is particularly useful for large datasets (like ours) where there exist many variables that might not have a strong statistical relationship with the dependent variable.[58]

Instead of running a LASSO regression on the hundreds of feature variables present in our dataset, we narrow our analysis by first excluding from the LASSO regression (1) binary variables indicating features that are available for all smartphone models in the dataset and thus have little or no variation in value,[59] (2) variables that have missing values for all smartphone models in the dataset,[60] and (3) variables that have missing values for

53 *See* Gujarati, Porter & Gunasekar, *supra* note 52, at 498; Wooldridge, *supra* note 52, at 84–86.

54 *See* Gujarati, Porter & Gunasekar, *supra* note 52, at 495–97; Wooldridge, *supra* note 52, at 84–86.

55 *See* Gujarati, Porter & Gunasekar, *supra* note 52, at 495–97; Wooldridge, *supra* note 52, at 84–86.

56 Wooldridge, *supra* note 52, at 804.

57 *See Least Absolute Shrinkage and Selection Operator (LASSO)*, Columbia University Mailman School of Public Health, *supra* note 51. In Stata, the "lassoregress" command standardizes the variables (that is, it places the variables on the same scale) before running the LASSO regression on the data.

58 *See id.*

59 These variables include *Cellular Connection (Y/N)*, *Network Generation*, *LTE (Y/N)*, *Primary Video Capture (Y/N)*, *Video Player (Y/N)*, *Speaker Phone*, *Instant Messaging*, *MMS*, *SMS*, *Email (Y/N)*, *Bluetooth (Y/N)*, *USB (Y/N)*, *Calendar*, and *Touchscreen (Y/N)*. Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

60 These variables include *General Comments*, *AMPS (Y/N)*, *iDEN (Y/N)*, *TDMA (Y/N)*, *AMPS 800/850 (Y/N)*, *AMPS 1900 (Y/N)*, *CDMA 900 (Y/N)*, *CDMA 1800 (Y/N)*, *iDen 800 (Y/N)*, *PDC (Y/N)*, *TDMA 800/850 (Y/N)*, *TDMA 1900 (Y/N)*, *UMTS 700 (Y/N)*, *UMTS 2600 (Y/N)*, *WiMAX (Y/N)*, *Carrier Aggregation Bands*, *Force Touch (Y/N)*, *Display Form Factor*, *Display Form Factor Details*, *Display FOV*, *EDoF (Y/N)*, *MediaFLO*, *DVB-H*, *CMMB*, *ISDB-T*, *FM Transmitter (Y/N)*, *SMAF*, *ROM (MB)*, *Hard Disk Drive (GB)*, *SDIO*, *Bundled Memory Card*, *SIM card memory*, *USB Ports*, *HDMI Version*, *Data Speed*, *CSD (Y/N)*, *HSCSD (Y/N)*, *BREW (Y/N)*, *WAP Version*, *WML (Y/N)*, *Adobe Flash Version*, *Adobe Flash Features*, *Currency Converter*, and *Humidity Sensor (Y/N)*. *Id.*

95 percent or more observations of all smartphone models in the dataset.[61] We also observe that there exist several groups of variables that are highly correlated (or "imperfectly multicollinear") with one another.[62] When two or more predictor variables are imperfectly multicollinear, the estimation of the coefficient on at least one of those predictor variables will be imprecise and the standard errors will tend to be inflated.[63] Thus, to avoid imperfect multicollinearity in our model, we include only one variable from each group of highly correlated variables in the LASSO regression. Furthermore, we exclude from the LASSO regression variables that for other reasons are likely to possess minimal explanatory power.[64]

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61 These variables include *Product Category*, *Number of Cells*, *Primary Display Colors*, *GSM (Y/N)*, *UMTS/WCDMA (Y/N)*, *CDMA 1700 (Y/N)*, *GSM 800/850 (Y/N)*, *GSM 1900 (Y/N)*, *UMTS/WCDMA 1800 (Y/N)*, *LTE-FDD (Y/N)*, *RCS (Y/N)*, *Antenna Type*, *Water Pressure Rating (atm)*, *4G Talk Time (min)*, *Touchscreen Technology*, *Keyboard*, *Solar Powered (Y/N)*, *Stylus*, *3D Display (Y/N)*, *Display Notch (Y/N)*, *Secondary Display (Y/N)*, *Secondary Display Type*, *Secondary Display Size Inch*, *Secondary Display Resolution*, *Secondary Display Colors*, *Camera (Y/N)*, *Primary Camera Type*, *Primary Camera Optical Zoom (Y/N)*, *Primary Camera Optical Zoom Strength*, *Autofocus (Y/N)*, *Secondary Camera (Y/N)*, *Secondary Camera Type*, *Flash*, *Video Call*, *DMB*, *H.264*, *Real Video*, *WBMP*, *iMelody*, *MP3*, *MP4*, *Real Audio*, *SMF*, *WAV*, *Push to Talk*, *Picture Messaging*, *EMS*, *Social Networking*, *Attach*, *Synch ML (Y/N)*, *Wi-Fi (Y/N)*, *802.11b (Y/N)*, *802.11g (Y/N)*, *802.11n (Y/N)*, *802.11ad (Y/N)*, *EDGE (Y/N)*, *GPRS (Y/N)*, *HSDPA (Y/N)*, *HSUPA (Y/N)*, *HSPA (Y/N)*, *WAP (Y/N)*, *XML (Y/N)*, *Phonebook Capacity, Adobe Flash (Y/N)*, *PIM (Y/N)*, *Alarm*, *Calculator*, *Clock*, *Games*, *GPS (Y/N)*, *Accelerometer (Y/N)*, *Proximity Sensor (Y/N)*, *Temperature Sensor (Y/N)*, *Pico Projector (Y/N)*, and *Form Factor Group*. *Id.*

62 For example, the correlation coefficient exceeds 0.8 for all possible pairs of variables within each of the following groups of variables: (1) *CDMA (Y/N)*, *CDMA 1900 (Y/N)*, *CDMA 2000 1xRTT (Y/N)*, and *CDMA 800/850 (Y/N)*, (2) *Voice Commands*, *Voice Dialing*, and *Voice Memo*, (3) *Dust Water Protection (Y/N)* and *Ruggedized (Y/N)*, (4) *2G Standby Time (Hr)*, *3G Standby Time (Hr)*, and *4G Standby Time (Hr)*, (5) *Pixels Per Inch (PPI)*, *Display Resn X*, and *Display Resn Y*, and (6) *Max DL Speed (Mbps)* and *Max UL Speed (Mbps)*. *Id.* Similarly, the *Weight (gr)* variable and the *Volume (cm3)* variable are highly correlated (with a correlation coefficient of 0.7348), and the *Volume (cm3)* variable and the *Thickness (mm)* variable are highly correlated (with a correlation coefficient of 0.7672). *Id.*

63 *See* James H. Stock & Mark W. Watson, Introduction to Econometrics 205 (Pearson 3d ed. 2015).

64 We exclude variables that reflect a device's compatibility with a particular format or subset of a more general smartphone feature, because those variables are unlikely to reflect general consumer purchase decisions. For example, when choosing between different models of smartphones, a consumer more likely will seek a device that can connect to Wi-Fi generally rather than a device that implements a specific Wi-Fi technology standard. Thus, we use the *Wi-Fi (Y/N)* variable rather than the *Wi-Fi 802.11a*, *Wi-Fi 802.11ac*, *Wi-Fi Hotspot (Y/N)*, and *Wi-Fi Direct (Y/N)* variables; the *GSM (Y/N)* variable rather than the *GSM 900 (Y/N)* and *GSM 1800 (Y/N)* variables; the *UMTS/WCDMA (Y/N)* variable rather than the *UMTS/WCDMA 800 (Y/N)*, *UMTS/WCDMA 850 (Y/N)*, *UMTS/WCDMA 900 (Y/N)*, *UMTS 1700 (Y/N)*, *UMTS/WCDMA 1900 (Y/N)*, and *UMTS/WCDMA 2100 (Y/N)* variables; the *Video Player (Y/N)* variable rather than the *GP*, *ASF*, *AVI*, *BMP*, *DivX*, *GIF*, *H.263*, *HEVC (H.265)*, *JPEG*, *MPEG4*, *PNG*, *WMV*, and *XviD* variables; the *Audio Features* variable rather than the *AAC*, *AAC+*, *eAAC*, *AMR*, *Midi*, and *WMA* variables; and the *Email (Y/N)* variable rather than the *IMAP4*, *POP3*, and *SMTP* variables. Ultimately, we drop the *Wi-Fi (Y/N)*, *GSM (Y/N)*, *UMTS/WCDMA (Y/N)*, and *Audio Feature* variables because more than 95 percent of smartphone models are equipped with those functionalities. We also ultimately drop the *Video Player (Y/N)* and *Email (Y/N)* variables because all smartphone models are equipped with those functionalities.

For groups of variables that might introduce multicollinearity (for example, because they measure similar features or because they are brand-specific features), we include only one variable in the LASSO regression. Thus, we use the *Ruggedized (Y/N)* variable rather than the *MIL-STD-810-G (Y/N)* variable; we use the *Maximum Card Size (GB)* variable rather than the *Memory Card Slot* variable; we exclude the *Heart Rate Sensor* variable (for which 56 of 57 observations are Samsung devices); we use the *Battery Capacity (mAh)* variable rather than the *Battery Voltage* and *Battery Wh (Wh)* variables; we use the *Primary Display Size (Inch)* variable rather than the *Screen to Body Ratio* variable; we exclude the *ANT (Y/N)* variable (for

After excluding variables with uniform, mostly uniform, or missing values, and after accounting for highly correlated variables, we run the LASSO regression on the remaining 56 variables.[65] We exclude the *NAND Flash (GB)* variable from the LASSO regression because it is a categorical variable—that is, a variable that "represents levels of some underlying factor."[66] In a regression model, each level of a categorical variable is included as a binary variable that equals one if the value equals that particular level and equals zero otherwise.[67] Because each level of a categorical variable is treated as an individual binary variable, a categorical variable is incompatible with this implementation of a LASSO regression. In other words, the LASSO regression is designed to select (or drop) an explanatory variable in its entirety, and not a particular level of that variable. Table 1 reports the results of the LASSO regression.

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which 90 of 92 observations are Samsung devices); we use the *Primary Camera Size (MP)* variable rather than the *Primary Camera 2 Size (MP)* and *Secondary Camera Size (MP)* variables; we use the *Processor Speed (MHz)* variable rather than the *Effective Clock Speed (MHz)* variable.

We also exclude the *Weight (gr)* variable. As we explained in Part I, earlier studies have obtained the counterintuitive result that a smartphone's weight has a positive and statistically significant relationship with a smartphone's price. Those studies speculate that that positive relationship results because a higher-priced smartphone is more likely than a lower-priced smartphone to contain (1) a higher-capacity battery, (2) a larger screen size, and (3) higher-quality casing and screen materials (such as metal, steel, and tempered glass, as opposed to plastic), all of which are positively correlated with a smartphone's weight. Using our dataset, we find (1) that the *Weight (gr)* variable and the *Battery Capacity (mAh)* variable are positively correlated with a correlation coefficient of 0.6499, and (2) that the *Weight (gr)* variable and the *Primary Display Size (Inch)* variable are positively correlated with a correlation coefficient of 0.5495. Because a smartphone's battery capacity and display size are more likely to influence a consumer's decision to purchase a particular smartphone relative to a smartphone's weight, we include in the LASSO regression the *Primary Display Size (Inch)* variable and the *Battery Capacity (mAh)* variable rather than the *Weight (gr)* variable. As we report in Appendix III, even when we *do* include the *Weight (gr)* variable in the LASSO regression, the estimated coefficient on the *Weight (gr)* variable is zero, indicating that that variable possesses little explanatory power for a smartphone's price. Furthermore, to test whether our model is robust to the exclusion of this variable, we run a regression for a specification of our hedonic price model that includes the *Weight (gr)* variable (in addition to the other variables included in the original specification of our hedonic price model). We report the results of that alternative specification in Appendix IV. In contrast to earlier studies that we describe in Part I, we find that the *Weight (gr)* variable has a negative but not statistically significant relationship with price in our hedonic price model when using nonimputed data, and that the variable has a negative and statistically significant relationship (at the 90-percent confidence level) with price in our hedonic price model when using imputed data. This result matches our expectations that, controlling for other features, consumers would value a lighter phone. Regardless of whether we use imputed data or nonimputed data, we find that the inclusion of the *Weight (gr)* variable in our hedonic price model does not alter our conclusion that a smartphone's brand possesses statistically significant explanatory power for a smartphone's price above and beyond a smartphone's functional features.

[65] These variables include *3G Talk Time (min)*, *Primary Video Frame Rate (fps)*, *Battery Capacity (mAh)*, *Primary Display Size (Inch)*, *Pixels Per Inch (PPI)*, *Primary Camera Size (MP)*, *Max DL Speed (Mbps)*, *Processor Speed (MHz)*, *Maximum Simultaneous Cores*, *Maximum Card Size (GB)*, *RAM (MB)*, *CDMA (Y/N)*, *LTE-A (Y/N)*, *TD-SCDMA (Y/N)*, *TD-LTE (Y/N)*, *VoLTE (Y/N)*, *VoWiFi (Y/N)*, *Ruggedized (Y/N)*, *Removable Battery (Y/N)*, *Wireless Charging (Y/N)*, *Pred Text (Y/N)*, *Dual Main Camera (Y/N)*, *Primary Camera Digital Zoom*, *TV Out (Y/N)*, *Handsfree*, *Voice Commands*, *Text to Speech (Y/N)*, *HD Voice (Y/N)*, *Bluetooth Low Energy (BLE) (Y/N)*, *Infrared (Y/N)*, *PC Synch (Y/N)*, *Microsoft Active Sync (Y/N)*, *USB Type-C (Y/N)*, *UMA (Y/N)*, *NFC*, *DLNA (Y/N)*, *HDMI (Y/N)*, *MHL (Y/N)*, *Wireless Display Support (Y/N)*, *FOTA (Y/N)*, *HTML (Y/N)*, *AI Assistant (Y/N)*, *ECML Digital Wallet*, *Organiser*, *Vibrate*, *Haptic Feedback*, *G-Sensor (Y/N)*, *Gyroscope (Y/N)*, *Magnetometer (Y/N)*, *Ambient Light Sensor (Y/N)*, *Pressure Sensor (Y/N)*, *Fingerprint Sensor (Y/N)*, *Gesture Sensor (Y/N)*, *Hall Sensor (Y/N)*, *Flash Light Torch*, and *TTY/TDD (Y/N)*.

[66] William H. Greene, Econometric Analysis 194 (Pearson 7th ed. 2012).

[67] *See id.*

Table 1. LASSO Regression Results
for Smartphone Prices

Variable	Estimated Coefficient
CDMA (Y/N)	0
LTE-A (Y/N)	50.97825
TD-SCDMA (Y/N)	0
TD-LTE (Y/N)	28.88796
VoLTE (Y/N)	0
VoWiFi (Y/N)	4.193028
Ruggedized (Y/N)	0
Removable Battery (Y/N)	−75.75001
Wireless Charging (Y/N)	0
Pred Text (Y/N)	0
Dual Main Camera (Y/N)	68.05674
Primary Camera Digital Zoom	34.87644
TV Out (Y/N)	125.8113
Handsfree	77.61186
Voice Commands	152.7513
Text to Speech (Y/N)	−20.48235
HD Voice (Y/N)	−26.97099
Bluetooth Low Energy (BLE) (Y/N)	0
Infrared (Y/N)	12.80762
PC Synch (Y/N)	44.73105
Microsoft Active Sync (Y/N)	0
USB Type-C (Y/N)	0
UMA (Y/N)	0
NFC	111.0268
DLNA (Y/N)	34.29581
HDMI (Y/N)	0
MHL (Y/N)	0
Wireless Display Support (Y/N)	−33.72669
FOTA (Y/N)	−41.26724
HTML (Y/N)	6.674135
AI Assistant (Y/N)	0
ECM Digital Wallet	0
Organiser	0

Vibrate	0
Haptic Feedback	−110.0153
G-Sensor (Y/N)	0
Gyroscope (Y/N)	37.94766
Magnetometer (Y/N)	0
Ambient Light Sensor (Y/N)	0
Pressure Sensor (Y/N)	129.6001
Fingerprint Sensor (Y/N)	−61.05685
Gesture Sensor (Y/N)	43.21653
Hall Sensor (Y/N)	−61.13251
Flash Light Torch	0
TTY/TDD (Y/N)	−29.13583
3G Talk Time (min)	0.0843343
Primary Video Frame Rate (fps)	−0.2740468
Battery Capacity (mAh)	−0.0418611
Primary Display Size (Inch)	30.9792
Pixels Per Inch (PPI)	0.7170097
Primary Camera Size (MP)	0
Max DL Speed (Mbps)	0.1879811
Processor Speed (MHz)	0
Maximum Simultaneous Cores	−11.99584
Maximum Card Size (GB)	−0.0465666
RAM (MB)	0
Constant	−160.1533
Observations	313
R^2	0.8627
alpha	1.0000
lambda	1.1230
Cross-validation Mean Squared Error	12763.2081

Source: STRATEGY ANALYTICS, SPECTRAX SERVICE, *supra* note 2, tab 2 ("Device Specifications").
Notes: The estimated coefficients reported in this table are strictly meant to guide the selection of explanatory variables and do not indicate the incremental value that consumers have demonstrated that they are willing to pay for a specific feature. We use an OLS regression to estimate that incremental value and report the results of that regression in Part II.C.

As Table 1 reports, the LASSO regression results show that 33 variables have a non-zero coefficient, meaning that those variables possess sufficient explanatory power for a smartphone's price to justify their inclusion in our hedonic price model. Although we exclude the *NAND Flash (GB)* categorical variable from the LASSO regression for reasons explained earlier, we find that the inclusion of that variable in our hedonic price model is justified because (1) the *NAND Flash (GB)* categorical variable has a statistically significant relationship with a smartphone's price[68] and (2) the variable adds explanatory power to our hedonic price model.[69]

In sum, we include in our hedonic price model (1) the 33 variables selected by the LASSO regression, (2) the *NAND Flash (GB)* categorical variable, and (3) indicator variables for each of the 40 brands of smartphones in the dataset to account for the idiosyncratic differences in value that consumers might assign to certain brands of smartphones.

C. *Testing the Hypothesis That a Smartphone's Brand Possesses Statistically Significant Explanatory Power Above and Beyond the Smartphone's Functional Features*

In Part II.B, we used the LASSO regression to select a combination of explanatory variables that best predicts a smartphone's price. Relying in part on the results of the LASSO regression, in this part we develop a hedonic price model to test the hypothesis that some consumers are willing to pay a premium for a smartphone's brand above and beyond the value attributable to the functional features of that smartphone. To test that hypothesis, we include in our hedonic price model indicator variables for each brand of smartphone in our dataset, in addition to the 33 LASSO-selected variables and the categorical variable for a smartphone's internal NAND Flash storage capacity. This hedonic price model enables us to test whether a smartphone's brand possesses statistically significant explanatory power above and beyond the functional features of a smartphone that best predict a smartphone's price, and we conclude that it does.

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[68] As we report in Appendix V, we perform a univariate regression of smartphone prices on the *NAND Flash (GB)* categorical variable and find that the estimated coefficient for 16GB of NAND flash memory is positive and statistically significant at the 95-percent confidence level, and that the estimated coefficients for 32GB, 64GB, 128GB, and 256GB of NAND flash memory are positive and statistically significant at the 99-percent confidence level.

[69] As we report later in Table 5, we find that the specification of our hedonic price model including the *NAND Flash (GB)* categorical variable has an R-squared value of 0.9313, which means that the model explains 93.13 percent of the variation in the smartphone price data. In contrast, as we report in Appendix VI, the specification of our hedonic price model that includes the same variables but ***excludes*** the *NAND Flash (GB)* categorical variable has an R-squared value of 0.9107, which means that that specification of the model explains 91.07 percent of the variation in the smartphone price data. We also find that higher levels of the *NAND Flash (GB)* categorical variable are statistically significant in the regression results reported in Table 5.

1. The Model to Derive the Value Attributable to Various Smartphone Features, Including Brand

Our hedonic price model is expressed in the following equation:

$$Price = a + \sum_{i=1,2,\ldots,33} (\beta_i \times LASSO\text{-}Selected\ Variable_i) + \beta_j \times NAND\ Flash\ (GB)_j + \sum_{k=1,2,\ldots,40} (\beta_k \times Brand_k) + \varepsilon, \tag{1}$$

where *Price* is the smartphone's unsubsidized retail price specified by the vendor, α is the constant term, $LASSO\text{-}Selected\ Variable_i$ indicates each of the 33 variables selected by the LASSO regression in Part II.B, $NAND\ Flash\ (GB)_j$ is a series of indicator variables for each level of memory capacity measured in gigabytes, and $Brand_k$ is a series of binary variables indicating each of the 40 brands of smartphones in our dataset.[70]

For each continuous variable, the estimated beta coefficient (β) measures the average incremental value that improving a given feature by one unit contributes to a consumer's demonstrated willingness to pay for a given smartphone model. For example, the beta coefficient for the *Pixels Per Inch (PPI)* variable measures the average effect that increasing display resolution by one PPI has on the price of a smartphone.

For the *NAND Flash (GB)* categorical variable, which is included as a series of indicator variables for each level of memory, β_j identifies the incremental value that having each level of memory (identified by the values of j) adds to the value of a smartphone relative to the base level (4GB), while holding all of the phone's other features constant. For example, the coefficient of the indicator variable for 64GB NAND Flash memory (which equals 0 when a smartphone model does not have 64GB NAND Flash memory and equals 1 when a smartphone model does have 64GB NAND Flash memory) reflects the average incremental amount that a consumer is willing to pay for a smartphone with 64 GB of NAND Flash memory relative to the base smartphone with 4GB of NAND Flash memory, holding all other features constant.

For each binary variable (which equals 0 when a smartphone model does not have a particular feature and equals 1 when the smartphone model does have that feature), the beta coefficient measures the average incremental value that incorporating that particular smartphone feature contributes to a

[70] Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications"). Because only Apple smartphones use the iOS operating system, the operating system of a smartphone is collinear with the brand of a smartphone. Consequently, we cannot distinguish the value attributable to the operating system of a smartphone from the value attributable to other brand-specific fixed effects. To allow for heterogeneity among the various brands of Android phones, we do not examine the value of a smartphone's operating system.

consumer's demonstrated willingness to pay for a smartphone. For example, β_k measures the incremental value that a consumer has demonstrated that she is willing to pay for a phone of a certain brand for each of the *k* brands, relative to a base brand (HTC), while holding all of the phone's other features constant. We use the HTC brand as the base brand because HTC had 31 different smartphone models with price data available for sale in the United States as of December 2018, and the average retail price of those smartphone models was $424.35, which is within one standard deviation of the average retail price of all smartphone models in the sample ($442.99).[71]

This hedonic price model enables us to identify consumers' demonstrated willingness to pay for various features and to separate the functionality of a particular smartphone from other non-functional factors that might affect its price, such as its perceived brand value.

2. *Summary Statistics for Variables Included in Our Hedonic Price Model*

Table 2 reports the summary statistics for each binary variable that we include in our hedonic price model.

[71] *Id.*

Table 2. Summary Statistics for Each Binary Variable Included in the Hedonic Price Model

Variable	Frequency of Smartphone Models Without the Feature	Frequency of Smartphone Models With the Feature	Total Number of Smartphone Models
LTE-A (Y/N)	400 (56.26%)	311 (43.74%)	711 (100.00%)
TD-LTE (Y/N)	384 (54.01%)	327 (45.99%)	711 (100.00%)
VoWiFi (Y/N)	584 (82.14%)	127 (17.86%)	711 (100.00%)
Removable Battery (Y/N)	587 (82.56%)	124 (17.44%)	711 (100.00%)
Dual Main Camera (Y/N)	620 (87.20%)	91 (12.80%)	711 (100.00%)
Primary Camera Digital Zoom	253 (35.58%)	458 (64.42%)	711 (100.00%)
TV Out (Y/N)	595 (83.68%)	116 (16.32%)	711 (100.00%)
Handsfree	605 (85.09%)	106 (14.91%)	711 (100.00%)
Voice Commands	104 (14.63%)	607 (85.37%)	711 (100.00%)
Text to Speech (Y/N)	658 (92.55%)	53 (7.45%)	711 (100.00%)
HD Voice (Y/N)	587 (82.56%)	124 (17.44%)	711 (100.00%)
Infrared (Y/N)	606 (85.23%)	105 (14.77%)	711 (100.00%)
PC Synch (Y/N)	113 (15.89%)	598 (84.11%)	711 (100.00%)
NFC	243 (34.18%)	468 (65.82%)	711 (100.00%)
DLNA (Y/N)	514 (72.29%)	197 (27.71%)	711 (100.00%)
Wireless Display Support (Y/N)	330 (46.41%)	381 (53.59%)	711 (100.00%)
FOTA (Y/N)	133 (18.71%)	578 (81.29%)	711 (100.00%)
HTML (Y/N)	73 (10.27%)	638 (89.73%)	711 (100.00%)

Haptic Feedback	140 (19.69%)	571 (80.31%)	711 (100.00%)
Gyroscope (Y/N)	238 (33.47%)	473 (66.53%)	711 (100.00%)
Pressure Sensor (Y/N)	531 (74.68%)	180 (25.32%)	711 (100.00%)
Fingerprint Sensor (Y/N)	338 (47.54%)	373 (52.46%)	711 (100.00%)
Gesture Sensor (Y/N)	611 (85.94%)	100 (14.06%)	711 (100.00%)
Hall Sensor (Y/N)	517 (72.71%)	194 (27.29%)	711 (100.00%)
TTY/TDD (Y/N)	546 (76.79%)	165 (23.21%)	711 (100.00%)

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Note: Most binary variables have values that either equal "Yes" or are missing, such that no values equal "No." For purposes of our analysis, we assume that all missing values indicate "No."

As Table 2 shows, the prevalence of each feature across smartphones varies. For example, 87.20 percent of the smartphone models in our dataset do not have the dual main camera feature, whereas 85.94 percent of smartphone models *do* have the gesture sensor feature. Some features (such as the fingerprint sensor feature and wireless display support feature) are available in roughly half of the smartphone models in our dataset.

Table 3 reports the summary statistics for the *NAND Flash (GB)* categorical variable that we include in our hedonic price model.

Table 3. Summary Statistics for the *NAND Flash (GB)* Categorical Variable Included in the Hedonic Price Model

Value of the *NAND Flash (GB)* Variable	Frequency of Smartphone Models
4	5 (0.70%)
8	80 (11.25%)
16	222 (31.22%)
32	219 (30.80%)
64	137 (19.27%)
128	35 (4.92%)
256	13 (1.83%)
Total	711

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

As Table 3 shows, we observe that 16GB is the most prevalent amount of NAND flash memory in our database of smartphones. Smartphones containing 16GB of NAND flash memory comprise 31.22 percent of all observations in our dataset. The second most prevalent amount of NAND flash memory is 32GB (30.80 percent), followed by 64GB (19.27 percent), 8GB (11.25 percent), 128GB (4.92 percent), 256GB (1.83 percent), and 4GB (0.70 percent).

Finally, Table 4 reports the summary statistics for each continuous variable that we include in our hedonic price model.

Table 4. Summary Statistics for Each Continuous Variable Included in the Hedonic Price Model

Variable	Observations	Median	Mean	Standard Deviation
3G Talk Time (min)	367	1020	1125.692	432.1804
Primary Video Frame Rate (fps)	622	30	33.11576	10.52056
Battery Capacity (mAh)	711	3000	2882.991	680.1341
Primary Display Size (Inch)	711	5.2	5.252768	0.4978505
Pixels Per Inch (PPI)	709	400.53	386.101	112.112
Max DL Speed (Mbps)	629	300	331.5164	282.78
Maximum Simultaneous Cores	711	4	4.578059	1.979976
Maximum Card Size (GB)	701	128	360.9244	648.2308

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

Although our dataset contains 711 observations of smartphone models with launch price information, we find that only 331 of those observations have information on every continuous variable that we include in our hedonic price model. The other 380 observations are missing information for at least one of the eight continuous variables that we include in our hedonic price model. Consequently, some of the rows in Table 4 report summary statistics for fewer than 711 observations of smartphone models.

3. *Results of Our Hedonic Price Regression on Smartphone Price Data*

In multivariate regression analysis, an estimation sample will exclude any observation that has only partial information—that is, an observation that is missing information for at least one of the model's variables.[72] Consequently, the estimation sample of a multivariate regression that we perform on our dataset would include only 331 observations for which complete information exists. It is possible that including only those 331 observations for which complete information exists in our estimation sample might produce biased results that are not representative of the entire population of smartphone models (which includes both observations with complete information and observations with partial information).[73]

As the number of variables included in a model increases, it becomes increasingly likely that fewer observations will be included in the estimation

[72] Wooldridge, *supra* note 52, at 314 ("If data are missing for an observation on either the dependent variable or one of the independent variables, then the observation cannot be used in a standard multiple regression analysis. In fact, provided missing data have been properly indicated, all modern regression packages keep track of missing data and simply ignore observations when computing a regression.").

[73] *See* Lu Ann Aday & Llewellyn J. Cornelius, Designing and Conducting Health Surveys: A Comprehensive Guide 350 (John Wiley & Sons 3d ed. 2006).

sample, because an observation will be excluded if it is missing information on even one of those variables. Some researchers might attempt to increase the estimation sample by reducing the number of variables that the model includes. However, because we seek to specify an objective model of a smartphone's price, we include every LASSO-selected variable in our model and examine an alternative method to mitigate the concern with a reduced sample size, rather than reduce the number of variables in our hedonic price model. In particular, we perform a regression by imputing missing data for the 380 observations that have partial information, such that our estimation sample includes all 711 observations of smartphone models. Specifically, we use the overall mean imputation method, which replaces the missing observations of each variable with the mean value of the non-missing observations of that variable.[74]

Table 5 reports the results of our hedonic price regression on the price data, showing how customers value a smartphone's various features and the brand value of a smartphone, relative to the base smartphone (that is, an HTC-brand smartphone with 4GB NAND Flash storage capacity). We report our regression results both (1) based on nonimputed data (which includes only smartphone models with complete information) in column 1 and (2) based on imputed data (which includes both smartphone models with complete information and those with partial information) in column 2.

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[74] *See id.* at 351. The variable that we are most interested in testing for statistical significance—a smartphone's brand—is never missing in our dataset.

Table 5. Hedonic Price Regression Results for Smartphone Launch Prices

Variable	Regression Based on Nonimputed Data	Regression Based on Imputed Data
LTE-A (Y/N)	47.2348*** (18.1996)	35.3580*** (13.4942)
TD-LTE (Y/N)	5.8623 (13.4134)	−16.4549* (9.7323)
VoWiFi (Y/N)	−45.7357** (21.8353)	−48.7108*** (15.9615)
Removable Battery (Y/N)	−61.0543*** (21.3383)	−39.3506*** (13.6778)
Dual Main Camera (Y/N)	36.2012 (23.7987)	−12.0416 (15.1174)
Primary Camera Digital Zoom	9.3950 (15.6760)	10.1908 (11.2549)
TV Out (Y/N)	78.1580*** (22.2858)	63.2184*** (15.9512)
Handsfree	41.3436** (20.4593)	32.7294** (16.1887)
Voice Commands	142.0157*** (42.9020)	107.6537*** (27.4674)
Text to Speech (Y/N)	20.7032 (29.3312)	35.0504 (21.7956)
HD Voice (Y/N)	42.5067** (19.4181)	6.0076 (13.2886)
Infrared (Y/N)	72.2019*** (24.0013)	89.2028*** (15.3371)
PC Synch (Y/N)	50.9499 (31.5331)	26.5866 (22.9603)
NFC	29.1555 (20.2166)	48.1306*** (13.2500)
DLNA (Y/N)	51.4799** (21.3224)	79.2503*** (14.4137)
Wireless Display Support (Y/N)	−69.1538*** (14.2898)	−29.9492*** (10.5869)
FOTA (Y/N)	−6.1473 (32.4838)	−14.9725 (24.2898)
HTML (Y/N)	41.5559 (40.8430)	42.8059** (18.1783)

Haptic Feedback		−142.1532***	−97.8073***
		(33.8939)	(26.7549)
Gyroscope (Y/N)		9.9983	16.9727
		(18.8212)	(14.2543)
Pressure Sensor (Y/N)		107.5538***	75.0562***
		(21.6778)	(15.3628)
Fingerprint Sensor (Y/N)		−68.9596***	−48.7961***
		(18.3469)	(13.0137)
Gesture Sensor (Y/N)		−7.4448	−18.6366
		(22.6622)	(15.0004)
Hall Sensor (Y/N)		−67.2767***	−22.9032*
		(17.8832)	(11.7719)
TTY/TDD (Y/N)		−9.5013	−15.4429
		(17.1434)	(13.3640)
3G Talk Time (min)[C]		0.0273	0.0422**
		(0.0243)	(0.0166)
Primary Video Frame Rate (fps)[C]		−0.3855	−0.3021
		(0.5477)	(0.4887)
Battery Capacity (mAh)[C]		−0.0165	−0.0076
		(0.0189)	(0.0116)
Primary Display Size (Inch)[C]		84.4025***	62.0354***
		(21.6457)	(14.5608)
Pixels Per Inch (PPI)[C]		0.8279***	0.6372***
		(0.0924)	(0.0617)
Max DL Speed (Mbps)[C]		0.1243***	0.1267***
		(0.0408)	(0.0286)
Maximum Simultaneous Cores[C]		−5.3307	−10.5322***
		(3.3191)	(2.5330)
Maximum Card Size (GB)[C]		−0.0193	−0.0106
		(0.0134)	(0.0081)
NAND Flash (GB)			
	8	−79.0918	19.1579
		(88.7711)	(47.9652)
	16	−34.3806	40.3568
		(89.8321)	(48.9503)
	32	−25.9483	65.1928
		(91.5715)	(50.9952)
	64	40.2973	124.0119**
		(92.7905)	(52.5742)
	128	115.9830	213.0594***
		(93.6278)	(55.2171)

	256	222.0765** (97.1359)	400.8248*** (61.6583)
Brand			
	Acer	–	−18.5965 (107.0333)
	Alcatel	−116.8565*** (42.2436)	−46.7974 (31.6435)
	Andy Rubin	–	237.5085** (108.3179)
	Apple	238.3294*** (48.3873)	299.3931*** (35.1997)
	Asus	−70.6361 (44.6131)	−45.8635 (32.9885)
	BlackBerry	63.3546 (44.0921)	126.8421*** (35.4504)
	Blackview	–	102.6413 (108.9630)
	BLU	−120.5218*** (39.4384)	−79.5368** (31.6276)
	Cat	19.3121 (101.8705)	213.9446*** (46.9331)
	CoolPAD	−194.5165* (101.8588)	−141.7976 (105.1390)
	Doro	–	−89.4023 (106.0624)
	Freetel	–	40.6799 (77.4159)
	Google	82.5084 (55.9176)	165.4592*** (43.7355)
	HP	–	225.1122** (109.8214)
	Huawei	−86.7011* (51.6442)	−33.3554 (29.4363)
	Kodak	–	264.8498** (106.2375)
	Kyocera	–	44.6163 (66.9648)
	LeEco	–	−236.9928** (106.5448)
	Lenovo	23.8248 (55.4466)	−13.0224 (28.1765)

	LG	−110.9331***	−42.1021*
		(40.0316)	(24.7573)
	Meitu	–	202.8408**
			(83.6207)
	Meizu	–	−77.0155
			(77.3097)
	Microsoft	−211.7718***	−127.7599**
		(60.9289)	(54.3493)
	Motorola	−9.7006	−19.5326
		(96.4850)	(38.8367)
	Nokia	14.8767	40.0600
		(42.7481)	(35.4345)
	OnePlus	–	−77.9807
			(50.1465)
	Plum	−67.8412	−76.3516
		(97.3443)	(105.6096)
	Razer	–	302.9332***
			(107.0985)
	Samsung	18.9959	56.8683**
		(33.4708)	(24.7873)
	Sky	–	−19.2090
			(54.7365)
	Sonim	–	436.6757***
			(88.6453)
	Sony	34.5849	25.0200
		(40.1189)	(28.8311)
	T-Mobile	24.3087	43.7713
		(100.5546)	(107.3600)
	Ulefone	–	−63.4662
			(82.1075)
	UMI Mobiles	–	10.3359
			(107.7340)
	Verykool	−0.6711	27.1279
		(71.0507)	(75.9181)
	Vivo	–	−38.4103
			(79.7382)
	Xiaomi	−74.9723	−141.0789***
		(102.6683)	(50.3046)
	ZTE	−166.8439***	−55.2414*
		(49.9576)	(32.6211)
Constant		−395.8151***	−371.1475***
		(132.8051)	(76.0988)

Observations	331	711
R^2	0.9313	0.8844
F-Statistic	61.03	62.01
Prob > F	0	0
Root Mean Squared Error	83.56	100.2

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Notes: * indicates statistical significance at the 90-percent confidence level, ** indicates statistical significance at the 95-percent confidence level, and *** indicates statistical significance at the 99-percent confidence level. ^{C} indicates that the variable is continuous.

In Table 5, a positive coefficient indicates the average incremental value that adding one unit of the feature (in the case of a continuous variable) or implementing the feature (in the case of a binary variable) contributes to a consumer's demonstrated willingness to pay for a smartphone model. For a feature that we include in our model as a continuous variable, a positive coefficient indicates that the greater the number of units of that feature that a smartphone incorporates, the higher the demonstrated price that a consumer is willing to pay for that smartphone. For example, the coefficient on the *Primary Display Size (Inch)* variable is positive and statistically significant at the 99-percent confidence level in both columns 1 and 2. These results indicate that consumers have demonstrated that they are willing to pay a positive and statistically significant amount to obtain a smartphone with a larger display size.

In contrast, a negative coefficient indicates the average incremental value that adding one unit of the feature (in the case of a continuous variable) or implementing the feature (in the case of a binary variable) *subtracts* from a consumer's demonstrated willingness to pay for a smartphone model. A negative coefficient does not necessarily imply that consumers have demonstrated that they are willing to pay to avoid implementing a feature in a smartphone, but rather that the feature might be less common in more expensive smartphone models.[75] Put differently, consumers of more expensive smartphone models might not value the feature as highly and therefore might be willing to forgo that feature. A smartphone manufacturer will include in a given smartphone model a finite number of features, likely subject to some technical constraint (such as the requirement to maintain a given amount of battery life) or physical constraint (such as the requirement that a smartphone weigh less than a given amount). Consequently, a manufacturer might include features that consumers value highly in a more expensive smartphone model,

[75] *See* Timothy Erickson, *On "Incorrect" Signs in Hedonic Regression* (U.S. Bureau of Labor Statistics Working Paper No. 490, July 2016).

at the expense of excluding other features that consumers might value less. In Table 5, the *Removable Battery (Y/N)* variable has a negative coefficient that is statistically significant at the 99-percent confidence level in both columns 1 and 2. These results indicate that removable batteries are implemented more frequently in less expensive smartphone models relative to more expensive smartphone models.

Some clinical researchers have expressed the concern that the overall mean imputation method might introduce bias into the estimation results.[76] To ensure that our imputation methodology does not introduce bias into the estimated coefficients, we compare the regression results based on imputed data with the regression results based on nonimputed data.[77] We find that the sign of the estimated coefficients remains consistent across both regressions for all variables except the *TD-LTE (Y/N)* variable, the *Dual Main Camera (Y/N)* variable, the indicator variables for 8GB, 16GB, and 32GB of NAND Flash memory, and the indicator variables for the Lenovo brand and Verykool brand. In six of the seven aforementioned instances in which the sign of the estimated coefficient does change across the two regressions, we observe that the estimated coefficient is statistically significant in neither regression. The *TD-LTE (Y/N)* variable is the only instance where the estimated coefficient both (1) changes in sign and (2) changes from being not statistically significant (in the regression based on nonimputed data) to statistically significant (in the regression based on imputed data). We test whether the two estimated coefficients are statistically significantly different from each other, and we find that they are not.[78] These results indicate that our imputation method does not introduce bias into our regression results.

As Table 5 shows, we find that many of the LASSO-selected variables are statistically significant when included in the hedonic price model and thus help predict the price of a smartphone. Most of the variables have coefficients that are similar in sign and magnitude whether we run the regression (1) using nonimputed data or (2) using imputed data. Our results indicate that consumers derive positive value from some features that are easily observable, such as a smartphone's display size (as measured in inches), screen resolution (as measured in pixels per square inch), and data speed (as measured by maximum downlink speed in megabits per second). Other features such as battery capacity and maximum card size are not individually statistically

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76 *See* A. Rogier T. Donders, Geert J.M.G. van der Heijden, Theo Stijnen & Karel G.M. Moons, *Review: A Gentle Introduction to Imputation of Missing Values*, 59 J. Clinical Epidemiology 1087, 1087 (2006).

77 *See* Aday & Cornelius, *supra* note 73, at 358 ("To attempt to minimize the possible biases in the estimates generated from the data, the investigator can use several different approaches to imputation, compare findings based on imputed and nonimputed data, and document whether the substantive results emanating from the various methods are confirmed.").

78 We obtain a chi-squared statistic of 3.30 and a *p*-value of 0.0691, which indicates that we cannot reject the null hypothesis that the two estimated coefficients are equal to each other at the five-percent confidence level.

significant in our hedonic price regression, although their selection by the LASSO regression algorithm indicates that those variables might jointly possess explanatory power for a smartphone's price. We test whether those variables that are not individually statistically significant in our hedonic price regression are *jointly* statistically significant, and we find that they are.[79]

Regardless of whether we use the imputed data or nonimputed data, we find that our hypothesis that a smartphone's brand possesses statistically significant explanatory power for a smartphone's price above and beyond a smartphone's functional features holds true. As column 1 in Table 5 reports, when we estimate the regression coefficients by using nonimputed data, we find that consumers have demonstrated that they are willing to pay a statistically significant premium for Apple ($238.33). As column 2 reports, when we estimate the regression coefficients by using imputed data, we find that consumers have demonstrated that they are willing to pay a statistically significant premium for brands including Andy Rubin ($237.51), Apple ($299.39), Blackberry ($126.84), Cat ($213.94), Google ($165.46), HP ($225.11), Kodak ($264.85), Meitu ($202.84), Razer ($302.93), Samsung ($56.89), and Sonim ($436.68) relative to the base brand (HTC) smartphone, holding all other smartphone features constant. Regardless of whether we use imputed data or nonimputed data, the regression results support the conclusion that at least some portion of the price that some consumers have demonstrated that they are willing to pay for a smartphone is attributable to factors unrelated to the smartphone's functionality, such as its brand.

To test the overall statistical significance of the original specification for our hedonic price model, we also perform a Wald test,[80] from which we obtain an F-statistic of 61.03 and a p-value of 0.0000 when not accounting

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[79] When we use the nonimputed data, we obtain an F-statistic of 1.69 and a p-value of 0.0482, which indicates that we can reject the null hypothesis (at the 95-percent confidence level) that those variables are jointly not statistically significant in our model. When we use the imputed data, we obtain an F-statistic of 4.64 and a p-value of 0.0000, which indicates that we can reject the null hypothesis (at the 99-percent confidence level) that those variables are jointly not statistically significant in our model.

[80] *See* Greene, *supra* note 66, at 155 ("The Wald test is the most commonly used procedure [for testing the hypothesis that an explanatory variable or group of explanatory variables is statistically significant]. It is often called a 'significance test.' The operating principle of the procedure is to fit the regression without the restrictions, and then assess whether the results appear, within sampling variability, to agree with the hypothesis."); Helvi Kyngäs & Marianne Rissanen, *Support as a Crucial Predictor of Good Compliance of Adolescents with a Chronic Disease*, 10 J. Clinical Nursing 767, 774 (2001) ("The Wald test is a way of testing the significance of particular explanatory variables in a statistical model. . . . If for a particular explanatory variable, or group of explanatory variables, the Wald test is significant, then we would conclude that the parameters associated with these variables are not zero, so that the variables should be included in the model. If the Wald test is not significant[,] then these explanatory variables can be omitted from the model."); *FAQ: How Are the Likelihood Ratio, Wald, and Lagrange Multiplier (Score) Tests Different and/or Similar?*, UCLA Institute for Digital Research and Education, http://stats.idre.ucla.edu/other/mult-pkg/faq/general/faqhow-are-the-likelihood-ratio-wald-and-lagrange-multiplier-score-tests-different-andor-similar/ ("The Wald test works by testing the null hypothesis that a set of parameters is equal to some value. . . . [T]he Wald test can be used to test multiple parameters simultaneously."); *see also* Stock & Watson, *supra* note 63, at 720 ("[T]he homoscedastic-only F-statistic . . . and the Wald F-statistic are two versions of the same statistic. That is, the two expressions are equivalent.").

for missing data and an *F*-statistic of 62.01 and a *p*-value of 0.0000 when accounting for missing data, as reported in columns 1 and 2 of Table 5. These results enable us to reject the null hypothesis that the results of our hedonic price regression are not statistically significant.[81] Put differently, a Wald test confirms the overall statistical significance of our hedonic price model and indicates that the observable characteristics of smartphones provide useful information to explain the variation in the prices for those smartphones.

Next, we examine the results of our hedonic price model to ensure that they meet the statistical assumptions for ordinary least squares regression and hypothesis testing.

III. Robustness of the Model to Derive the Brand Value Attributable to Various Smartphones

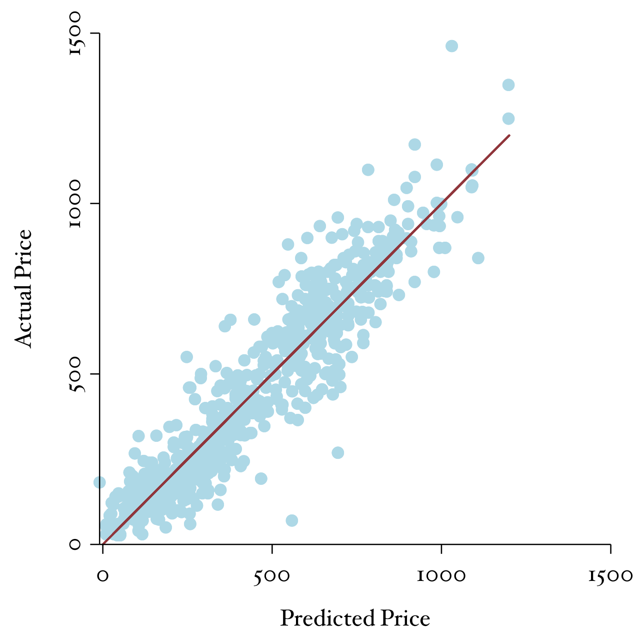
We now examine several alternative specifications of our hedonic price model to test whether our finding that consumers are willing to pay a premium for certain smartphone brands is robust to alternative specifications of the econometric model, such as the inclusion of different variables to measure each smartphone's features. We find that our result is robust to these tests, and we confirm our hypothesis that a large portion of the retail prices for certain brands is attributable to brand value, which is *not* related to the value attributable to the functionality of smartphones. On the basis of these robustness checks, we confirm that consumers derive some incremental value from various features and brands of smartphones, as manifested by their demonstrated willingness to pay for those features and brands.

A. Does Our Hedonic Price Model Accurately Predict Smartphone Prices?

To assess whether our hedonic price model accurately predicts the price of a smartphone, in Figure 5 we compare actual smartphone prices with smartphone prices as predicted by our hedonic price model by plotting actual price on the *y*-axis and predicted price on the *x*-axis.

[81] The *F*-statistic indicates whether our hedonic regression model has any explanatory power. *See* Wooldridge, *supra* note 52, at 147 ("This null hypothesis is, in a way, very pessimistic. It states that *none* of the explanatory variables has any effect on *y*." (emphasis in original)); *see also* David R. Anderson, Dennis J. Sweeney & Thomas A. Williams, Statistics for Business and Economics 658 (South-Western 11th ed. 2011) ("The *F* test is used to determine whether a significant relationship exists between the dependent variable and the set of all independent variables.").

Figure 5. Distribution of Actual Smartphone Price and Predicted Smartphone Price

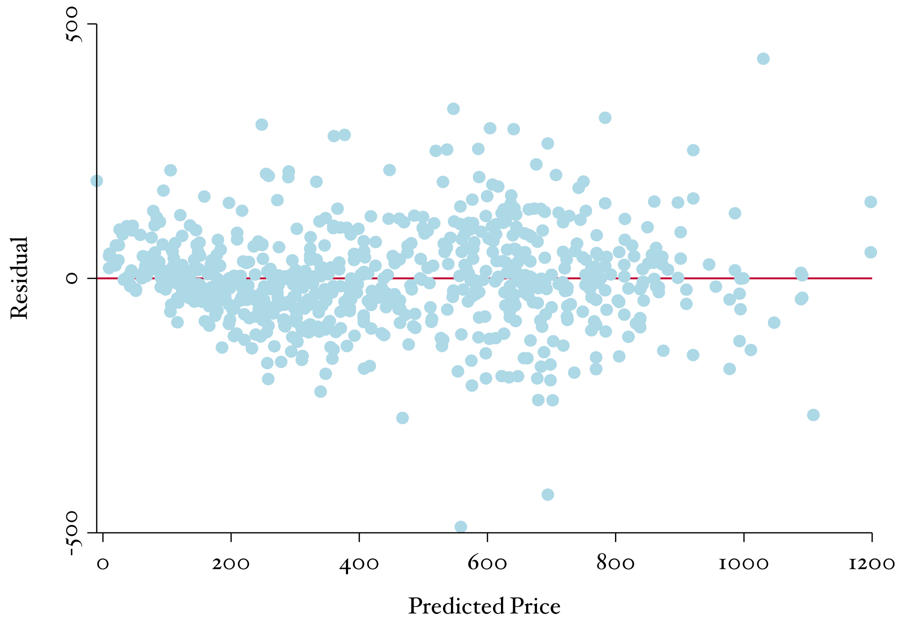


Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Notes: The LG Tribute Dynasty SP200 is the only smartphone model in our dataset that has a negative predicted price. That smartphone model has an actual price of $182 as of December 2018. *Id.* However, because it possesses multiple features that are prevalent in cheaper phones (such as a removable battery and the haptic feedback feature) and thus have negative coefficients in our hedonic price model, its predicted price is negative.

As Figure 5 shows, the scatterplot generally follows the 45-degree line (along which actual price equals predicted price), indicating that our model is generally accurate in predicting a smartphone's price based on the selected features and that the selected features can explain phone prices across the price spectrum, from the least-expensive smartphones to the most-expensive smartphones. In Figure 5, the vertical distance between each plotted predicted price and the 45-degree line represents the residual—that is, the difference between actual price and predicted price.

Figure 6 plots the residual values on the *y*-axis and predicted price on the *x*-axis to examine whether the distribution of residuals is biased. That is, we examine whether our model systematically overestimates or underestimates smartphone price.

Figure 6. Distribution of Residuals Across Predicted Values of Smartphone Price



Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

Table 6 reports summary statistics for the residual values plotted in Figure 6.

Table 6. Summary Statistics for Residual Values

Observations	711
Mean	4.99×10^{-7}
Median	−2.685865
Standard Deviation	94.51374
25th Percentile	−51.20398
75th Percentile	47.12769

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

As Figure 6 and Table 6 show, the residual values are distributed around zero and do not display evidence of heteroskedasticity—that is, they do not display evidence that the variance of residuals is nonconstant[82]—indicating that our hedonic price model does not produce biased results and that we can use common hypothesis-testing methods to evaluate the statistical significance of our model's results.

82 Stock & Watson, *supra* note 63, at 774.

B. *The Robustness of Our Conclusions to Alternative Specifications of the Hedonic Price Model*

Here, we present four alternative specifications of our hedonic price model and examine whether the results of the original specification of our hedonic price analysis are robust to those alternative specifications. We first explain each of those alternative specifications of our hedonic price model and subsequently report the results for those alternative specifications in Table 9.

1. *Testing Whether the Hedonic Price Model Is Robust to the Inclusion of Only "Key" Features of Smartphones*

Our hedonic price model includes several explanatory variables for a smartphone's price, including the 33 LASSO-selected variables, the *NAND Flash (GB)* categorical variable, and indicator variables for each brand of smartphone available in our dataset. However, a consumer who wishes to purchase a smartphone might not consider all of those features when choosing among different models of smartphones. Thus, we also examine the alternative specification of our hedonic price model including only "key features" of a smartphone as identified by market research firms.

Strategy Analytics identifies the following features as "key specifications" of mobile devices: LTE bands, network generation, thickness, weight, battery capacity, primary display size, primary display resolution, primary camera resolution, RAM, NAND flash, maximum downlink speed, maximum uplink speed, applications processor vendor, and applications processor chip.[83] We modify this list of key features for purposes of our analysis. First, because we have already limited our dataset to 4G smartphones available in the United States, we exclude the *Network Generation* variable and the *LTE Bands* variable (which indicates the frequency of the LTE network) from the alternative specification of our model. We also exclude the weight variable from the alternative specification of our model because, as explained in Part II.B, the weight variable (1) is positively correlated with a smartphone's battery capacity and display size and (2) possesses little explanatory power for a smartphone's price, as demonstrated by the zero coefficient on the weight variable in the LASSO regression.[84] We exclude the thickness variable because it is highly correlated with the volume variable, which in turn is highly correlated with a smartphone's weight.[85] We also exclude maximum uplink speed from the alternative specification of our model because it is highly correlated with maximum downlink speed, as explained in Part II.B. Finally, because a typical

[83] Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 1.
[84] *See supra* note 64.
[85] *See supra* note 62.

consumer of smartphones is unaware of the type or the vendor of applications processor embedded in the device, we include processor speed (which consumers more directly observe when making purchasing decisions) in our alternative specification rather than the applications processor vendor and applications processor chip. We find that including only these key features of smartphones in our hedonic price model does not alter our conclusion that brand value accounts for a considerable portion of a smartphone's price. We report the results of this alternative specification of our hedonic price model in column 3 of Table 9.

2. *Testing Whether the Hedonic Price Model Is Robust to the Exclusion of the* 3G Talk Time (min) *Variable*

The *3G Talk Time (min)* variable is missing in 48.38 percent of all observations in our dataset.[86] We also observe that the *3G Talk Time (min)* variable has a correlation coefficient of 0.7066 with the *Battery Capacity (mAh)* variable.[87] Thus, we analyze whether excluding the *3G Talk Time (min)* variable from our model (and thereby increasing the size of our estimation sample with non-imputed data) materially changes the results of our analysis. We find that, regardless of whether we include or exclude the *3G Talk Time (min)* variable from our model, our conclusion that brand value accounts for a considerable portion of a smartphone's price (above the value of features related to functionality) still holds. We report the results of this alternative specification of our hedonic price model in column 4 of Table 9.

3. *Testing Whether the Hedonic Price Model Is Robust to Smartphone "Tiers"*

Industry sources generally classify smartphones into different "tiers" on the basis of price. For example, Strategy Analytics defines the "Product Tier" of each smartphone model in the dataset on the basis of the price of the smartphone. Table 7 reports the range of prices corresponding to each tier of smartphone, as defined by Strategy Analytics.

[86] *Id.* tab 2 ("Device Specifications").
[87] *Id.*

Table 7. Product Tiers as Defined by Strategy Analytics

Product Tier	Launch Price Range
Entry	< $100
Mid	$100–$300
High	$300–$400
Premium	$400–$500
Ultra Premium	≥ $500

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

One might contend that a consumer who purchases an "Ultra Premium" tier smartphone model exhibits different purchasing behavior and preferences than a consumer who purchases an "Entry" tier smartphone model (although we disagree with that assertion).[88] For example, a consumer of "Ultra Premium" smartphones might be willing to pay a higher price for a particular brand of smartphone. In addition, an "Ultra Premium" tier device might incorporate more advanced functional features than an "Entry" tier device.

Thus, to test whether our hedonic price model is robust to the categorization of smartphone models based on such smartphone tiers, we analyze whether limiting the sample to only smartphones that Strategy Analytics labels as "Ultra Premium" alters the conclusions of our analysis. We find that restricting the regression sample to "Ultra Premium" phones does not alter our conclusion that the prices of many smartphone devices include the value attributable to brand name. In addition, we find that several of the variables that measure the functional features of a smartphone are still statistically

[88] From an economic perspective, it would be non-rigorous to define a product market around a subset of smartphones on the basis of such tiers. First, the definition of such tiers is not uniform across industry sources. For example, whereas Strategy Analytics' highest tier of smartphones has prices that equal or exceed $500 (as shown in Table 7), IDC, another market research firm, reports that "ultra-high end" smartphones have prices that equal or exceed $700. *See* Press Release, IDC, Smartphone Rankings Shaken Up Once Again as Huawei Surpasses Apple, Moving into Second Position While Overall Market Declined 1.8% in Q2 2018, According to IDC (July 31, 2018), https://www.idc.com/getdoc.jsp?containerId=prUS44188018. Consequently, a given smartphone might fall under a different tier depending on the particular definition of smartphone tier used.

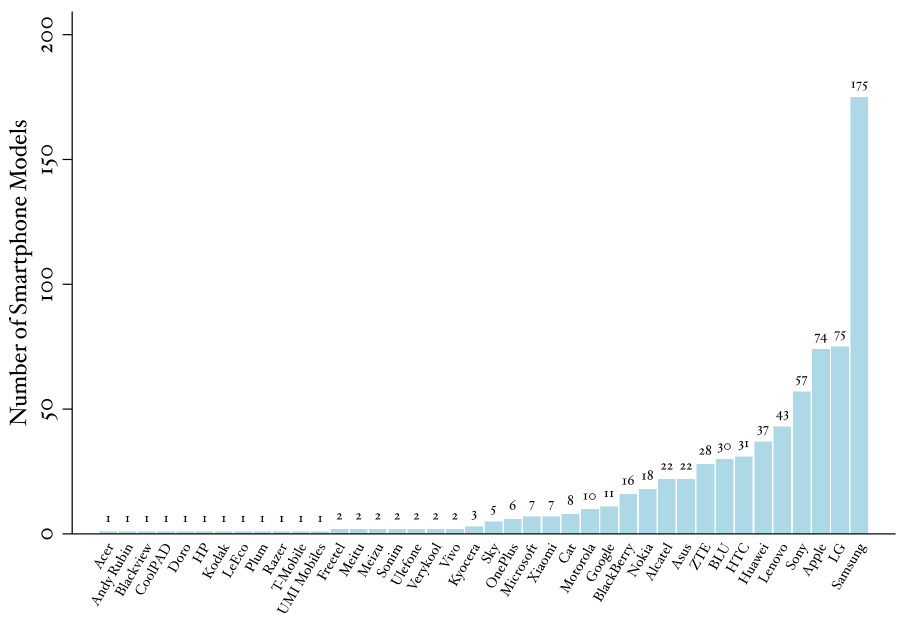
Second, the arbitrary and formalistic categorization of smartphones into different tiers does not necessarily inform what consumers consider to be substitutes for a given device. Suppose that a consumer wants to buy a new smartphone and her top choice is device A, which has a price of $410 and is thus categorized as a "premium"-tier smartphone by Strategy Analytics. Suppose further that device A becomes unavailable. From an economic perspective, the consumer will choose the next-best available substitute for device A. In the absence of any further facts, there is no reason to assume that that consumer, who was willing to spend $410 for device A, will be more willing to turn to a $499 phone than to a $399.99 phone (which, according to Strategy Analytics' classification, is a "high"-tier phone but not a "premium"-tier phone) if device A becomes unavailable. Thus, there is no valid economic reason to expect that consumers will not consider a given device to be a substitute for another device unless the two devices belong to the same tier. Future research could apply hedonic price analysis to examine whether a consumer might consider a particular smartphone model to be a substitute for another model. However, that analysis exceeds the scope of this article.

significant under that alternative specification of the model. We report the results of this alternative specification of our hedonic price model in column 5 of Table 9.

4. *Testing Whether the Hedonic Price Model Is Robust to the Exclusion of Brands with Fewer Than Three Observations of Smartphone Models*

We observe that 19 of the 40 brands present in our dataset offer fewer than 3 models of smartphones in the United States. Specifically, Acer, Andy Rubin, Blackview, CoolPAD, Doro, HP, Kodak, LeEco, Plum, Razer, T-Mobile, and UMI Mobiles offer only one smartphone model, and Freetel, Meitu, Meizu, Sonim, Ulefone, Verykool, and Vivo offer only two smartphone models. Figure 7 shows the number of smartphone models offered by each brand, ranked from the lowest number of smartphone models to the highest number of smartphone models.

Figure 7. Number of Smartphone Models Offered by Each Brand, Ranked

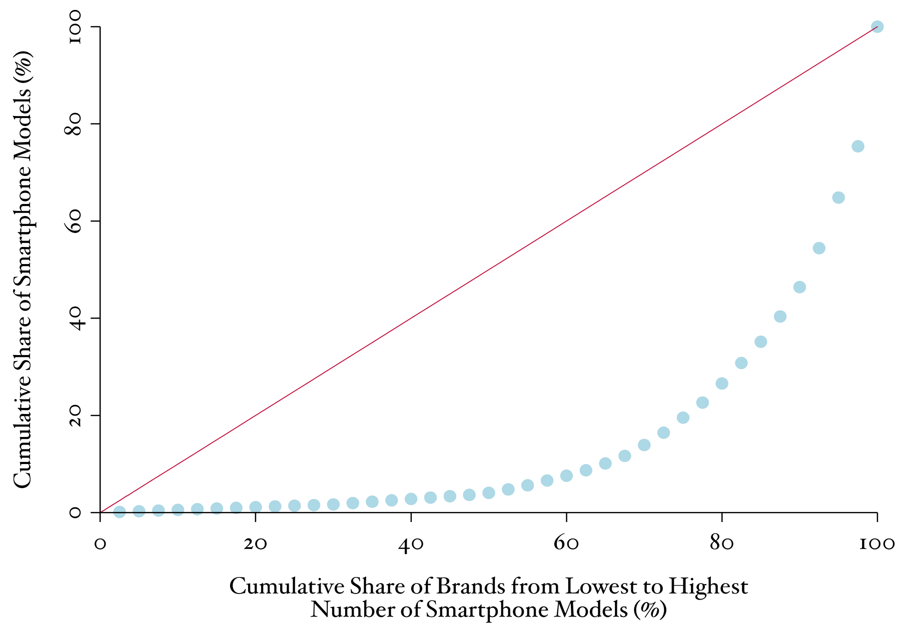


Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

As Figure 7 shows, the number of smartphone models is concentrated among a few brands, such that those few brands account for a high proportion of the total number of available smartphone models. To analyze the inequality in the distribution of the number of smartphone models, we also plot a Lorenz curve,[89] a tool that economists use to measure the inequality in distributions, such as the distribution of income within and among nations.[90]

Figure 8 shows a Lorenz curve with the cumulative share of smartphone models on the *y*-axis and the cumulative share of brands from lowest to highest number of smartphone models on the *x*-axis.

Figure 8. Lorenz Curve for the Distribution of Smartphone Models Across Brands



Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").

In Figure 8, the 45-degree line (represented by the diagonal red line) is the line that would be drawn if each brand offered the same number of smartphone models. The degree to which the Lorenz curve deviates from the 45-degree line is a measure of the inequality of the distribution of the number of smartphone models across brands. The convex shape of the dotted curve (the Lorenz curve) in Figure 8 indicates that the number of smartphone models is not distributed equally across brands.

[89] For the definition of the Lorenz curve, see N.C. Kakwani, *Applications of Lorenz Curves in Economic Analysis*, 45 Econometrica 719, 719 (1977) ("The Lorenz curve relates the cumulative proportion of income units to the cumulative proportion of income received when units are arranged in ascending order of their income."); Daniel B. Levine & Neil M. Singer, *The Mathematical Relation Between the Income Density Function and the Measurement of Income Inequality*, 38 Econometrica 324, 324 (1970) ("The Lorenz curve exhibits income distribution by plotting the interdependence of . . . the percentage of total income earned by the percentage of population.").

[90] *See, e.g.*, Kakwani, *supra* note 89, at 719; Martin Bronfenbrenner, Income Distribution Theory 47–50 (Aldine Transaction 1971).

To account for the possibility that brands that offer fewer models of smartphones are specialized (for example, for military use) and therefore do not represent the general population of smartphone models available to consumers, in an alternative specification of our hedonic price model, we test whether this inequality in the distribution of the number of smartphone models affects the results of our analysis. Put differently, we test whether the exclusion of smaller brands from our estimation sample affects the results of our analysis. We find that excluding smaller brands from our regression sample does not alter our conclusion that the prices of many smartphone devices include the value that consumers attribute to brand name. We report the results of this alternative specification of our hedonic price model in column 6 of Table 9.

5. *Summary of Robustness Checks*

In sum, to test the robustness of our hedonic price analysis, we analyze alternative forms of our hedonic price model, including (1) the alternative specification including only key features of smartphones, (2) the alternative specification excluding the *3G Talk Time (min)* variable, (3) the alternative specification using only smartphone models that Strategy Analytics defines as "Ultra Premium," and (4) the alternative specification excluding brands with fewer than three smartphone models in the dataset. For each of these alternative specifications, we include only smartphone models with complete information for each of the variables included in the model. Put differently, we do not impute missing values for smartphones containing only partial information.

Table 8 reports the summary statistics for each continuous variable that we include in the alternative specifications of our hedonic price model.

Table 8. Summary Statistics for Each Continuous Variable Included in Alternative Specifications of the Hedonic Price Model

Variable	Observations	Median	Mean	Standard Deviation
*3G Talk Time (min)**	367	1020	1125.692	432.1804
*Primary Video Frame Rate (fps)**	622	30	33.11576	10.52056
*Battery Capacity (mAh)**	711	3000	2882.991	680.1341
*Primary Display Size (Inch)**	711	5.2	5.252768	0.4978505
*Pixels Per Inch (PPI)**	709	400.53	386.101	112.112
*Max DL Speed (Mbps)**	629	300	331.5164	282.78
*Maximum Simultaneous Cores**	711	4	4.578059	1.979976
*Maximum Card Size (GB)**	701	128	360.9244	648.2308
Primary Camera Size (MP)	711	13	12.70633	4.25849
RAM (MB)	706	3072	2725.382	1274.131
Processor Speed (MHz)	693	1800	1781.804	453.6366

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Note: * indicates that the variable is also included in the original specification of our hedonic price model.

In Table 9, we present the results of the four alternative specifications (in columns 3 through 6), as well as the results of our original specifications reported earlier in Part II.C.3 (in columns 1 and 2 of Table 5).

Table 9. Hedonic Price Regression Results for Smartphone Prices, Original and Alternative Specifications

Variable	Original Specification (Missing Data Not Imputed) [1]	Original Specification (Missing Data Imputed) [2]	Robustness Check #1: “Key” Smartphone Features Only [3]	Robustness Check #2: Excluding *3G Talk Time (min)* [4]	Robustness Check #3: “Ultra Premium” Smartphones Only [5]	Robustness Check #4: Excluding Brands with Fewer Than 3 Smartphone Models [6]
LTE-A (Y/N)	47.2348*** (18.1996)	35.3580*** (13.4942)	–	33.9222** (14.4200)	40.2375 (41.1284)	47.1978** (18.2261)
TD-LTE (Y/N)	5.8623 (13.4134)	−16.4549* (9.7323)	–	−11.1569 (10.2303)	−21.3646 (22.7121)	6.0046 (13.4362)
VoWiFi (Y/N)	−45.7357** (21.8353)	−48.7108*** (15.9615)	–	−40.4784** (16.1564)	−24.4339 (38.9369)	−45.6875** (21.8672)
Removable Battery (Y/N)	−61.0543*** (21.3383)	−39.3506*** (13.6778)	–	−36.1222** (15.0399)	45.1720 (64.2464)	−60.6182*** (21.3893)
Dual Main Camera (Y/N)	36.2012 (23.7987)	−12.0416 (15.1174)	–	4.1715 (15.7761)	16.9724 (31.8055)	36.3369 (23.8349)
Primary Camera Digital Zoom	9.3950 (15.6760)	10.1908 (11.2549)	–	3.0553 (12.3570)	38.5210 (32.3530)	9.2227 (15.7029)
TV Out (Y/N)	78.1580*** (22.2858)	63.2184*** (15.9512)	–	47.8808*** (16.6449)	37.2714 (27.9689)	78.0039*** (22.3204)
Handsfree	41.3436** (20.4593)	32.7294** (16.1887)	–	34.8102** (16.8309)	41.9691 (29.6399)	41.3642** (20.4889)
Voice Commands	142.0157*** (42.9020)	107.6537*** (27.4674)	–	147.8052*** (31.0123)	–	143.7955*** (43.1309)
Text to Speech (Y/N)	20.7032 (29.3312)	35.0504 (21.7956)	–	12.4267 (23.1260)	−11.4119 (47.2368)	20.4915 (29.3771)
HD Voice (Y/N)	42.5067** (19.4181)	6.0076 (13.2886)	–	6.3125 (13.5496)	57.9049* (31.7166)	42.5893** (19.4469)
Infrared (Y/N)	72.2019*** (24.0013)	89.2028*** (15.3371)	–	104.9425*** (17.5298)	−26.3260 (39.6539)	72.7509*** (24.0645)
PC Synch (Y/N)	50.9499 (31.5331)	26.5866 (22.9603)	–	32.8681 (26.0935)	−95.2004 (128.4036)	52.1649 (31.6845)
NFC	29.1555 (20.2166)	48.1306*** (13.2500)	–	35.1068** (14.4641)	−37.6973 (91.3077)	29.2104 (20.2461)
DLNA (Y/N)	51.4799** (21.3224)	79.2503*** (14.4137)	–	77.8320*** (15.5659)	11.1342 (55.0019)	51.5498** (21.3538)
Wireless Display Support (Y/N)	−69.1538*** (14.2898)	−29.9492*** (10.5869)	–	−37.5729*** (11.3021)	−81.2465*** (29.2686)	−69.4387*** (14.3233)
FOTA (Y/N)	−6.1473 (32.4838)	−14.9725 (24.2898)	–	−17.2652 (26.5210)	−60.9325 (89.7443)	−6.0986 (32.5310)

Variable	Original Specification (Missing Data Not Imputed) [1]	Original Specification (Missing Data Imputed) [2]	Robustness Check #1: "Key" Smartphone Features Only [3]	Robustness Check #2: Excluding *3G Talk Time (min)* [4]	Robustness Check #3: "Ultra Premium" Smartphones Only [5]	Robustness Check #4: Excluding Brands with Fewer Than 3 Smartphone Models [6]
HTML (Y/N)	41.5559 (40.8430)	42.8059** (18.1783)	–	61.8736** (27.2388)	197.5845* (101.1738)	40.8169 (40.9324)
Haptic Feedback	−142.1532*** (33.8939)	−97.8073*** (26.7549)	–	−117.3105*** (28.4514)	43.3915 (68.4716)	−142.6893*** (33.9621)
Gyroscope (Y/N)	9.9983 (18.8212)	16.9727 (14.2543)	–	11.8716 (14.9159)	–	10.1166 (18.8501)
Pressure Sensor (Y/N)	107.5538*** (21.6778)	75.0562*** (15.3628)	–	86.7229*** (16.0214)	64.2044 (45.5463)	107.3111*** (21.7153)
Fingerprint Sensor (Y/N)	−68.9596*** (18.3469)	−48.7961*** (13.0137)	–	−51.3706*** (13.7484)	−159.9005*** (40.0118)	−68.6353*** (18.3865)
Gesture Sensor (Y/N)	−7.4448 (22.6622)	−18.6366 (15.0004)	–	−20.4495 (15.8968)	−13.0100 (41.5524)	−7.3823 (22.6953)
Hall Sensor (Y/N)	−67.2767*** (17.8832)	−22.9032* (11.7719)	–	−28.1552** (13.0693)	−68.8133 (54.1593)	−67.1488*** (17.9112)
TTY/TDD (Y/N)	−9.5013 (17.1434)	−15.4429 (13.3640)	–	−3.5047 (13.8355)	−16.2683 (28.3083)	−9.6144 (17.1699)
3G Talk Time (min)	0.0273 (0.0243)	0.0422** (0.0166)	–	–	−0.1540*** (0.0555)	0.0271 (0.0244)
Primary Video Frame Rate (fps)	−0.3855 (0.5477)	−0.3021 (0.4887)	–	−0.0019 (0.4804)	−0.1257 (0.6771)	−0.3819 (0.5486)
Battery Capacity (mAh)	−0.0165 (0.0189)	−0.0076 (0.0116)	−0.0019 (0.0142)	0.0005 (0.0116)	0.1067** (0.0432)	−0.0167 (0.0189)
Primary Display Size (Inch)	84.4025*** (21.6457)	62.0354*** (14.5608)	33.2082* (19.7580)	77.0482*** (16.9715)	66.7436 (44.7011)	85.0509*** (21.7209)
Pixels Per Inch (PPI)	0.8279*** (0.0924)	0.6372*** (0.0617)	0.9333*** (0.0812)	0.7062*** (0.0680)	0.5792** (0.2681)	0.8264*** (0.0926)
Max DL Speed (Mbps)	0.1243*** (0.0408)	0.1267*** (0.0286)	0.0676* (0.0354)	0.1065*** (0.0310)	0.0921* (0.0548)	0.1241*** (0.0408)
Maximum Simultaneous Cores	−5.3307 (3.3191)	−10.5322*** (2.5330)	–	−9.3946*** (2.5419)	−15.5261* (8.5181)	−5.3572 (3.3244)
Maximum Card Size (GB)	−0.0193 (0.0134)	−0.0106 (0.0081)	–	−0.0003 (0.0087)	0.0154 (0.0259)	−0.0194 (0.0134)
Primary Camera Size (MP)	–	–	3.2441 (2.2155)	–	–	–
RAM (MB)	–	–	−0.0319*** (0.0104)	–	–	–

Variable	Original Specification (Missing Data Not Imputed) [1]	Original Specification (Missing Data Imputed) [2]	Robustness Check #1: "Key" Smartphone Features Only [3]	Robustness Check #2: Excluding *3G Talk Time (min)* [4]	Robustness Check #3: "Ultra Premium" Smartphones Only [5]	Robustness Check #4: Excluding Brands with Fewer Than 3 Smartphone Models [6]
Processor Speed (MHz)	–	–	0.1501*** (0.0235)	–	–	–
NAND Flash (GB)						
8	−79.0918 (88.7711)	19.1579 (47.9652)	21.5952 (77.5608)	−34.2220 (69.7197)	–	−78.4641 (88.9095)
16	−34.3806 (89.8321)	40.3568 (48.9503)	31.1513 (77.6074)	2.6083 (69.9314)	–	−34.1207 (89.9638)
32	−25.9483 (91.5715)	65.1928 (50.9952)	43.1358 (80.2384)	18.3154 (71.5561)	38.2037* (21.9934)	−25.6866 (91.7057)
64	40.2973 (92.7905)	124.0119** (52.5742)	91.6953 (82.3425)	65.7592 (72.6669)	109.2320*** (22.7438)	40.4418 (92.9252)
128	115.9830 (93.6278)	213.0594*** (55.2171)	214.8055** (85.2462)	159.4344** (74.4832)	174.7583*** (24.7033)	116.2647 (93.7652)
256	222.0765** (97.1359)	400.8248*** (61.6583)	395.6275*** (97.2142)	288.7970*** (79.3010)	274.3724*** (32.9637)	222.2416** (97.2770)
Brand						
Acer	–	−18.5965 (107.0333)	–	–	–	–
Alcatel	−116.8565*** (42.2436)	−46.7974 (31.6435)	−116.5138*** (40.2106)	−62.2572* (33.9209)	–	−117.0106*** (42.3060)
Andy Rubin	–	237.5085** (108.3179)	162.8897 (134.2294)	225.5938** (102.9526)	–	–
Apple	238.3294*** (48.3873)	299.3931*** (35.1997)	282.4458*** (34.9850)	303.8255*** (36.6321)	224.7296*** (80.2481)	238.3269*** (48.4573)
Asus	−70.6361 (44.6131)	−45.8635 (32.9885)	−139.6649*** (40.5309)	−82.2212** (35.5917)	34.9277 (134.7132)	−70.6664 (44.6777)
BlackBerry	63.3546 (44.0921)	126.8421*** (35.4504)	37.3511 (51.7712)	72.0926* (42.3353)	−31.7337 (78.3842)	63.4190 (44.1561)
Blackview	–	102.6413 (108.9630)	−63.2397 (136.8615)	–	–	–
BLU	−120.5218*** (39.4384)	−79.5368** (31.6276)	−161.5788*** (37.5329)	−103.2738*** (33.6071)	–	−120.6091*** (39.4959)
Cat	19.3121 (101.8705)	213.9446*** (46.9331)	96.5755 (67.8442)	136.1939** (55.3064)	–	20.4487 (102.0466)
CoolPAD	−194.5165* (101.8588)	−141.7976 (105.1390)	−221.8465* (132.2345)	−132.6587 (102.1277)	–	–
Doro	–	−89.4023 (106.0624)	–	–	–	–

Variable	Original Specification (Missing Data Not Imputed) [1]	Original Specification (Missing Data Imputed) [2]	Robustness Check #1: "Key" Smartphone Features Only [3]	Robustness Check #2: Excluding *3G Talk Time (min)* [4]	Robustness Check #3: "Ultra Premium" Smartphones Only [5]	Robustness Check #4: Excluding Brands with Fewer Than 3 Smartphone Models [6]
Freetel	–	40.6799 (77.4159)	−227.9921* (132.9416)	25.5382 (103.1499)	–	–
Google	82.5084 (55.9176)	165.4592*** (43.7355)	200.3101*** (48.8781)	167.1821*** (45.3062)	157.0324* (80.0508)	82.0810 (56.0059)
HP	–	225.1122** (109.8214)	162.4815 (133.7811)	190.9302* (104.4668)	–	–
Huawei	−86.7011* (51.6442)	−33.3554 (29.4363)	−76.5579** (36.0672)	−77.0924** (33.4582)	–	−86.4841* (51.7210)
Kodak	–	264.8498** (106.2375)	–	–	–	–
Kyocera	–	44.6163 (66.9648)	31.3088 (80.0801)	16.9440 (64.7138)	–	–
LeEco	–	−236.9928** (106.5448)	−278.9914** (131.7565)	−249.9708** (101.2380)	–	–
Lenovo	23.8248 (55.4466)	−13.0224 (28.1765)	−125.7946*** (34.3226)	−33.0466 (29.9892)	123.2666 (108.9875)	23.9040 (55.5271)
LG	−110.9331*** (40.0316)	−42.1021* (24.7573)	−69.8606** (31.1710)	−100.6014*** (29.3012)	−345.0189*** (96.3679)	−111.8081*** (40.1328)
Meitu	–	202.8408** (83.6207)	–	–	–	–
Meizu	–	−77.0155 (77.3097)	–	–	–	–
Microsoft	−211.7718*** (60.9289)	−127.7599** (54.3493)	−70.3075 (56.0205)	−164.2729*** (54.2403)	−370.5630*** (108.4833)	−212.2835*** (61.0268)
Motorola	−9.7006 (96.4850)	−19.5326 (38.8367)	−83.3331 (51.6134)	−31.4158 (40.2816)	22.6182 (134.4055)	−9.7513 (96.6246)
Nokia	14.8767 (42.7481)	40.0600 (35.4345)	−23.7092 (41.0328)	4.4870 (36.7590)	39.5873 (106.3754)	14.5601 (42.8152)
OnePlus	–	−77.9807 (50.1465)	−35.4557 (69.1218)	−87.2754* (49.6160)	–	–
Plum	−67.8412 (97.3443)	−76.3516 (105.6096)	−133.4491 (132.8702)	−34.9486 (100.5444)	–	–
Razer	–	302.9332*** (107.0985)	–	–	–	–
Samsung	18.9959 (33.4708)	56.8683** (24.7873)	18.1090 (28.4257)	43.6112 (27.4116)	27.9540 (52.4642)	18.7690 (33.5227)
Sky	–	−19.2090 (54.7365)	−135.0827 (82.9858)	–	–	–

Variable	Original Specification (Missing Data Not Imputed) [1]	Original Specification (Missing Data Imputed) [2]	Robustness Check #1: "Key" Smartphone Features Only [3]	Robustness Check #2: Excluding *3G Talk Time (min)* [4]	Robustness Check #3: "Ultra Premium" Smartphones Only [5]	Robustness Check #4: Excluding Brands with Fewer Than 3 Smartphone Models [6]
Sonim	–	436.6757*** (88.6453)	–	–	–	–
Sony	34.5849 (40.1189)	25.0200 (28.8311)	−15.3246 (35.5184)	8.9085 (30.3667)	−35.1034 (54.8145)	34.8055 (40.1797)
T-Mobile	24.3087 (100.5546)	43.7713 (107.3600)	−164.0979 (132.5559)	−6.2270 (100.8748)	–	–
Ulefone	–	−63.4662 (82.1075)	−235.2425* (140.1407)	–	–	–
UMI Mobiles	–	10.3359 (107.7340)	–	–	–	–
Verykool	−0.6711 (71.0507)	27.1279 (75.9181)	−28.6322 (96.6247)	11.4043 (72.9127)	–	–
Vivo	–	−38.4103 (79.7382)	−144.3294 (96.3675)	−38.6455 (76.3284)	–	–
Xiaomi	−74.9723 (102.6683)	−141.0789*** (50.3046)	−196.5674** (97.0245)	−129.8410* (76.4080)	–	−72.9812 (102.9042)
ZTE	−166.8439*** (49.9576)	−55.2414* (32.6211)	−173.6014*** (44.7656)	−97.4006** (39.5007)	–	−167.3429*** (50.0411)
Constant	−395.8151*** (132.8051)	−371.1475*** (76.0988)	−381.3626** (106.9913)	−425.8371*** (99.4070)	−75.2139 (217.6280)	−399.8678*** (133.2770)
Observations	331	711	608	571	149	326
R^2	0.9313	0.8844	0.7839	0.8995	0.8796	0.9294
F-Statistic	61.03	62.01	46.42	68.33	16.21	63.20
Prob > F	0	0	0	0	0	0
Root Mean Squared Error	83.56	100.2	128.6	92.95	66.76	83.68

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Notes: * indicates statistical significance at the 90-percent confidence level, ** indicates statistical significance at the 95-percent confidence level, and *** indicates statistical significance at the 99-percent confidence level.

As Table 9 reports, regardless of the chosen specification of our hedonic price model, Apple commands a statistically significant premium for its brand relative to the base brand (HTC) smartphone, keeping all other features constant. Similarly, Google commands a statistically significant premium for its brand in all regression models except those reported in column 1 (the original specification of our hedonic price model based on nonimputed data) and column 6 (which excludes brands with fewer than three smartphone models), relative to the base brand (HTC) smartphone, keeping all other features constant. Similarly, the *Pixels Per Inch (PPI)* variable and the *Max DL Speed (Mbps)* variable possess a statistically significant positive value in all specifications of the hedonic price model, indicating that those features are among the most explanatory of a smartphone's price.

We observe fewer features with a statistically significant effect on price in the alternative specification of the hedonic price model that includes only "Ultra Premium" smartphones, the results of which we report in column 5. We obtain this result likely because that alternative specification of the hedonic price model includes only 149 observations, which is fewer than half of the 331 observations included in the original specification of the hedonic price model based on nonimputed data (the results of which we report earlier in Part II.C.3). When testing whether an estimated coefficient is statistically significant, one typically examines the *t*-statistic, which is inversely proportional to the standard error.[91] A higher *t*-statistic indicates that the estimated coefficient is statistically significant at a higher confidence level. The "standard error" of an estimated coefficient—that is, an estimate from a particular sample of the standard deviation in the estimated coefficient[92]—equals the sample standard deviation divided by the square root of the number of observations in the sample.[93] Thus, holding all other factors constant, a smaller estimation sample will produce estimated coefficients with a higher standard error and, consequently, a lower statistical significance. Indeed, we observe that the standard error associated with the estimated coefficient of each variable in the model that includes only "Ultra Premium" smartphones exceeds the standard error associated with that particular variable in the original specification of our hedonic price model, except in the case of the *NAND Flash (GB)* categorical variable. We observe a lower standard error associated with the *NAND Flash (GB)* categorical variable in the model that includes only "Ultra Premium" smartphones because the deviation in the levels of NAND Flash memory among "Ultra Premium" smartphones is lower than the deviation in the levels of NAND Flash memory among all smartphones.

[91] Stock & Watson, *supra* note 63, at 76.
[92] *Id.* at 75.
[93] *Id.*

Conclusion

By regressing a multicomponent product's total price on the product's individual features, hedonic price analysis enables one to determine how much consumers are willing to pay for each observable feature of a multicomponent product, including a product's brand. In this article, we conduct hedonic price analysis to test whether a smartphone's brand name possesses statistically significant explanatory power for a smartphone's price that is unrelated to the technical functionality of the smartphone, and we find that it does. As of April 2019, this article is the first publicly reported hedonic price analysis of the demand for features of smartphones in the United States that uses the "least absolute shrinkage and selector operator" (LASSO) regression—an objective variable selection method based on a machine learning algorithm—to identify the functional features that are the best predictors of a smartphone's price.

Appendix I. Description of Each Smartphone Feature Included in Strategy Analytics' SpecTRAX Database

Field Name	Description (by Strategy Analytics)
SpecTRAX ID	A unique identifier for each device on the database
Brand	The vendor's name
Model Name	The name of the device model
Phone Name	="Brand" + "Model Name"
Model Family Name	Used to group similar devices from the same vendor under a common name (eg Galaxy S)
Phone Name Comments	Comments on the name of the device.
FCC Approval	ID given by FCC
Month Added to Database	Self-explanatory
Date Announced	The quarter in which the handset was announced
Date Launched	The quarter in which the handset first became available through a network operator
Current Status	Describes whether "Active", "Pre-launch", "Discontinued", "Cancelled"
Product Type	Broad categorisation of product type
Product Category	A subjective detailed categorisation of the market positioning of the device, based on specs and the vendor's advertising
Country of Origin	In which country is the headquarters of the brand
Launch Price	The recommended retail price [at launch] (if given by the vendor) unsubsidised
Launch Price Range	Converted into dollars
Product Tier	Not currently used
General Comments	Self-explanatory
Variant Identifier	Detailed information showing whether the device variant is designed to work in a specific country or on a specific network
Cellular Connection	Does the device have cellular capabilities?
Network Generation	Used to categorise the device as 3G or 3.5G etc
Multi SIM	How many SIM cards does the device support?
Multi Standby	For multi-SIM swapping, eg Dual standby, single standby
AMPS (Y/N)	'Yes' if one of the AMPS fields equals Yes.
CDMA (Y/N)	'Yes' if one of the CDMA fields equals Yes.
GSM (Y/N)	'Yes' if one of the GSM fields equals Yes.
iDEN (Y/N)	'Yes' if one of the iDEN fields equals Yes.
TDMA (Y/N)	'Yes' if one of the TDMA fields equals Yes.
UMTS / WCDMA (Y/N)	'Yes' if one of the UMTS / WCDMA fields equals Yes.

LTE (Y/N)	Yes if one of the LTE fields equals Yes.
LTE-A (Y/N)	Yes if the handset supports LTE Advanced
AMPS 800 / 850 (Y/N)	Yes if the handset supports AMPS 800 or AMPS 850
AMPS 1900 (Y/N)	Yes if the handset supports AMPS 1900
CDMA 800 / 850 (Y/N)	Yes if the handset supports CDMA 800 or CDMA 850
CDMA 900 (Y/N)	Yes if the handset supports CDMA 900
CDMA 1700 (Y/N)	Yes if the handset supports CDMA 1700
CDMA 1800 (Y/N)	Yes if the handset supports CDMA 1800
CDMA 1900 (Y/N)	Yes if the handset supports CDMA 1900
GSM 800 / 850 (Y/N)	Yes if the handset supports GSM 800 or GSM 850
GSM 900 (Y/N)	Yes if the handset supports GSM 900
GSM 1800 (Y/N)	Yes if the handset supports GSM 1800
GSM 1900 (Y/N)	Yes if the handset supports GSM 1900
iDen 800 (Y/N)	Yes if the handset supports iDen 800
PDC (Y/N)	Yes if the handset supports PDC
TDMA 800 / 850 (Y/N)	Yes if the handset supports TDMA 800 or TDMA 850
TDMA 1900 (Y/N)	Yes if the handset supports TDMA 1900
UMTS 700 (Y/N)	Yes if the handset supports UMTS / WCDMA 700
UMTS / WCDMA 800 (Y/N)	Yes if the handset supports UMTS / WCDMA 800
UMTS / WCDMA 850 (Y/N)	Yes if the handset supports UMTS / WCDMA 850
UMTS / WCDMA 900 (Y/N)	Yes if the handset supports UMTS / WCDMA 900
UMTS 1700 (Y/N)	Yes if the handset supports UMTS / WCDMA 1700
UMTS / WCDMA 1800 (Y/N)	Yes if the handset supports UMTS / WCDMA 1800
UMTS / WCDMA 1900 (Y/N)	Yes if the handset supports UMTS / WCDMA 1900
UMTS / WCDMA 2100 (Y/N)	Yes if the handset supports UMTS / WCDMA 2100
UMTS 2600 (Y/N)	Yes if the handset supports UMTS / WCDMA 2600
TD-SCDMA (Y/N)	Yes if the handset supports TD-SCDMA
WiMAX (Y/N)	Yes if the handset supports WiMAX
LTE-FDD (Y/N)	Yes if the handset supports Frequency Division LTE
TD-LTE (Y/N)	Yes if the handset supports Time Division LTE
VoLTE (Y/N)	Yes if the device supports VoIP over LTE
VoWIFI (Y/N)	Yes if the device supports Voice over WiFi
RCS (Y/N)	Yes if the device supports Rich Communication Systems
LTE Bands	A list of the LTE bands (from 1 to 40+) supported by the device
Carrier Aggregation Bands	A list of the LTE bands that support Carrier Aggregation
Network Comments	Text comments relating to networks supported
Form Factor	Physical shape of the handset

Dimensions (mm)	In the format: height x width x thickness
Thickness (mm)	the thickness of the handset in mm
Volume (cm3)	calculated as height * width * thickness or recorded as a value if specified
Weight (gr)	handset weight including standard battery
Antenna Type	Typically internal these days
SIM Card Size	What size SIM card does the device support
Device Color	A list of the colors the device is available in
Ruggedized (Y/N)	Does the device have protection against water/dust/impact?
MIL-STD-810G (Y/N)	Does the device support the military standard 810G?
Dust/Water Protection (Y/N)	Does the device have protection against water and/or dust?
IP Dust Protection Rating	What is the full ingress protection dust rating of the device
IP Water Protection Rating	What is the full ingress protection water rating of the device
Water Pressure Rating (atm)	What are the pressure/depth and time ratings for the waterproofness of the device
Default Case Materials	What are the main materials used in the body of the device, eg glass, aluminium, wood, plastic
Physical Comments	Includes comments such as colours available or metallic finishes
Battery Type	Chemistry of the standard battery
Removable Battery (Y/N)	Can the battery be removed from the device by the user?
Number of Cells	How many battery cells (in series or parallel) are in the device?
Battery Voltage	What is the nominal voltage of the single cell or battery combination?
Battery Capacity (mAh)	Capacity of the standard battery
Battery Wh (Wh)	Capacity of the standard battery in Watt-hours
2G Standby Time (Hr)	Maximum standby time in hours of the standard battery as specified by the manufacturer
2G Talk Time (min)	Maximum talk time in minutes of the standard battery as specified by the manufacturer
3G Standby Time (Hr)	Maximum standby time in hours of the standard battery as specified by the manufacturer
3G Talk Time (min)	Maximum talk time in minutes of the standard battery as specified by the manufacturer
4G Standby Time (Hr)	Maximum standby time in hours of the standard battery as specified by the manufacturer
4G Talk Time (min)	Maximum talk time in minutes of the standard battery as specified by the manufacturer
Music Playback Time (Hrs)	Maximum time in hours of the standard battery as specified by the manufacturer

Video Playback Time (Hr)	Maximum time in hours of the standard battery as specified by the manufacturer
Web Browsing Time (Hr)	Maximum time in hours of the standard battery as specified by the manufacturer
Runtime (Hr)	Maximum time in hours of the standard battery as specified by the manufacturer
Wireless Charging (Y/N)	Maximum talk time in minutes of the standard battery as specified by the manufacturer
Solar Powered (Y/N)	Does the device have built-in solar panels for charging?
Charging Method	If the device supports fast charge, which method is employed, eg Quick Charge, VOOC…
Battery Comments	Includes specs such as music playback time, video recording time, teleconference time where available
Keyboard	Type of keyboard/keypad. In the process of being updated from a text field to a list validation field
Stylus	Can the device be operated with (and does it come with) a stylus/pen?
Pred Text (Y/N)	Does the device support predictive text?
Pred Text Type	Type of predictive text, eg T9, eZi
Input Comments	Includes comments such as handwriting recognition, hard keys for camera/music functions
Primary Display Type	Technology of the primary display, typically TFT LCD, CSTN LCD or OLED.
3D Display (Y/N)	Does the display support autostereoscopic 3D viewing?
Display Notch (Y/N)	Does the display include and integrated notch?
Primary Display Size (Inch)	Diagonal size of main display, expressed as a number
Screen-to-Body Ratio	Display size as percentage of device footprint (to one decimal place)
Primary Display Resolution	In the format "320 x 240 Pixels"
Primary Display Aspect Ratio	What is the ratio between the display height and width. An asterix (*) indicates that the pixels are oblong, not square.
Display Resn X	What is the horizontal resolution of the display
Display Resn Y	What is the vertical resolution of the display
Pixels Per Inch (PPI)	What is the pixel density of the display?
Primary Display Colors	In the format 65,536 or 262,144 or 16,777,216 colours for example
Touchscreen (Y/N)	Does the screen support touch input
Touchscreen Technology	Which touchscreen technology is used
Force Touch (Y/N)	Does the display support force/pressure detection. Details given in Display Comments.
Secondary Display (Y/N)	Does the device have a secondary display, eg as in clamshall handsets
Secondary Display Type	What is the technology of the secondary display

Secondary Display Size (Inch)	Diagonal size of secondary display, expressed as a number
Secondary Display Resolution	In the format "320 x 240 Pixels"
Secondary Display Colors	In the format 65,536 or 262,144 or 16,777,216 colours for example
Display Form Factor	What shape is the display?
Display Form Factor Details	Does the Display have curved edges or is it flat?
Display FOV	Display Field of View angle
Display Comments	Includes comments such as the touchscreen technology type (eg capacitive) where known
Camera (Y/N)	Does the handset support a camera? Yes/No
Primary Camera Type	Is the camera integrated, attachable, fixed or swivel?
Primary Camera Sensor Type	What is the technology of the primary camera sensor?
Dual Main Camera (Y/N)	Does the device have 2 main cameras?
Primary Camera Size (MP)	How many megapixels is the camera sensor
Primary Camera Resolution	In the format "2560 x 1920 Pixels"
Primary Camera Optical Zoom (Y/N)	Does the camera module support optical zoom
Primary Camera Optical Zoom Strength	What strength is the optical zoom, eg 2x, 3x
Primary Camera Digital Zoom	What strength is the digital zoom, eg 3x, 4x, 8x
Primary Camera 2 Size	For devices with dual main camera, what is the resolution (in megapixels) of the second camera sensor?
Flash	Does the camera module support a camera flash
Autofocus (Y/N)	Does the camera module incorporate an autofocus facility
EDoF (Y/N)	Does the camera module use Extended Depth of Field? (a software alternative to the mechanical autofocus)
Secondary Camera (Y/N)	If applicable, normally an inward facing lower-resolution camera used for video-conferencing
Secondary Camera Type	Is the secondary camera integrated, attachable, fixed or swivel?
Secondary Camera Sensor Type	What is the technology of the secondary camera
Secondary Camera Size (MP)	How many megapixels is the secondary camera sensor
Secondary Camera Resolution	In the format "640 x 480 Pixels"
Primary Video Capture (Y/N)	Does the device support video capture?
Primary Video Resolution (pixels)	eg "640 x 480 Pixels" video capture resolution
Primary Video Frame Rate (fps)	eg 15, to represent 15 frames per second
Streaming Video	"Yes" if the handset supports streaming video, the ability to display real-time content over the network
Video Call	"Yes" if the handset supports two-way video conversations
Video Player (Y/N)	Does the device play video?
Video Player Details	Details
Camera and Video Comments	Includes comments such as face detection, blink detection, where known

MediaFLO	Broadcast TV standard developed by Qualcomm, using its own network frequencies
DVB-H	Digital Video Broadcasting - Handheld. Broadcast TV standard developed by the DVB Organisation
CMMB	China Multimedia Mobile Broadcasting based on the 2.6GHz frequency
DMB	Digital Multimedia Broadcasting. Korean TV standard. Includes sattelite (S-DMB) and terrestrial (T-DMB)
ISDB-T	Integrated Services Digital Broadcasting - Terrestrial. Japanese TV standard, includes 1seg.
TV Details	Includes additional details such as 1seg, T-DMB.
TV Out (Y/N)	The ability to connect the device to a television using a cable for streaming content
3GP	Multimedia container format for use on 3G devices. Similar to MPEG-4 Part 14
ASF	Advanced Systems Format. Proprietary Microsoft audio/video container format
AVI	Audio Video Interleave, a multimedia container format developed by Microsoft
BMP	Bitmap image format
DivX	A video compression standard
GIF	Graphics Interchange Format
H.263	Video codec standard originally developed for teleconferencing
H.264	A video compression standard
HEVC (H.265)	High Efficiency Video Codec standard
JPEG	Joint Photographic Experts Group. Compression standard used for photographic images
MPEG4	A collection of video, audio and speech compression standards
PNG	Portable Network Graphics. A bitmapped image format superceding GIF.
Real Video	Proprietary video format developed by RealNetworks. Suitable for use in streaming video
WBMP	Officially "Wireless Application Protocol Bitmap Format" or simply wireless bitmap. A monochrome graphics file format
WMV	Windows Media Video. A compressed video file format.
XviD	A video compression standard
Video Format Comments	Includes additional detail such as Real video v7, v8, v9, v10, GIF87a, GIF89a, TIFF
Radio	Includes FM Radio, Stereo FM Radio, Digital radio, RDS
FM Transmitter (Y/N)	Does the device incorporate an FM transmitter, used in-car to send audio feed to the car's radio

Headset	Description of the physical characteristics of the headset socket, eg 3.5mm jack, proprietary jack
Speaker	Description of the support for mono or stereo speakers
Audio Features	Additional comments
Audio Comments	Additional comments such as 3D surround sound
AAC	Advanced Audio Coding. An audio compression format.
AAC+	AAC+ is the term used by Nokia, Sony Ericsson and Samsung for High-Efficiency AAC V1.
eAAC+	Enhanced AAC+ is the term used by Nokia, Sony Ericsson and Samsung for High-Efficiency AAC V2.
AMR	Adaptive multi-rate compression. Optimised for speech compression.
iMelody	Ringtone format developed by Ericsson
Midi	Musical Instrument Digital Interface. A control protocol.
MP3	Also known as MPEG-1 Audio Layer 3.
MP4	Also known as MPEG-4 Part 14. A multimedia container format.
Real Audio	Proprietary Audio format developed by RealNetworks. Suitable for use in streaming audio and music
SMAF	Synthetic Music Mobile Application Format. A music data format developed by Yamaha. Suitabel for ringtones
SMF	Standard MIDI File.
WAV	Waveform Audio format. A file format for uncompressed audio developed by Microsoft and IBM.
WMA	Windows Media Audio. Proprietary audio data compression technology developed by Microsoft
Audio Format Comments	Includes additional information on audio formats supported.
Push to Talk	PTT. A half-duplex communication system like walkie-talkie
Speaker Phone	Yes if the device includes a speaker that can be used during voice calls to enable the device to be held away from the ear
Handsfree	Yes if the device can be used with a hands-free kit in a car
Voice Commands	Uses speech recognition to initiate actions on the device hands-free
Voice Dialing	Uses speech recognition to enable a call to be initiated by speaking the contact's name
Voice Memo	Yes if the device can be used like a dictaphone to record short messages
Text to Speech (Y/N)	Does the device support TTS for message reading, Caller ID, Navigation or Song Information?
HD Voice (Y/N)	Does the device support High Definition voice calls
Voice Comments	Includes additional information on audio features, such as which text to speech software is installed?

Instant Messaging	Yes if the device supports Yahoo, MSN Messenger, ICQ, AOL etc for internet-based chat
Picture Messaging	Does the device support picture messaging?
EMS	Enhanced Messaging Service. Enables small photos, graphics, audio etc to be sent to a contact. Not as powerful as MMS
MMS	Multimedia Messaging Service. Enables long text messages and the sending of photos, videos and audio clips
SMS	Short Message Service. The ability to send and receive short text messages.
Social Networking	Ability to support sites like Facebook, MySpace, Bebo, Twitter
Messaging Comments	Additional comments such as which instant messaging software is supported, and details of social networking support
Email (Y/N)	Does the device support sending/receiving of emails?
IMAP4	Internet Message Access Protocol.
POP3	Post Office Protocol. An email protocol
SMTP	Simple Mail Transfer Protocol. Complimentary to POP and IMAP.
Attach	Does the device's email client support attachments?
Email Comments	Includes details of the specific email service supported eg Gmail, Yahoo, Outlook, AIM and attachment size
RAM (MB)	Random Access Memory (volatile)
ROM (MB)	Read Only Memory (non-volatile) typically used for system memory
NAND Flash (GB)	User memory
Hard Disk Drive (GB)	Does the device contain an HDD type of storage
Internal Memory Comments	Details of the RAM and ROM capacity
Memory Card Slot	Does the device support a removable memory card?
SDIO	Secure Digital Input/Output.
Memory Card Slot Type	Card slot format. T-Flash or Translfash are coded as microSD
Maximum Card Size (GB)	What is the maximum capacity of removable memory card that the device can support?
Bundled Memory Card	What, if any, size memory card is bundled as standard with the device
SIM card memory	Can the SIM card store a significant amount of user data?
Memory Comments	Includes maximum card capacity, eg 8GB, where available
Bluetooth (Y/N)	Does the device support the Bluetooth standard
Bluetooth Version	Which version does it support
Bluetooth Low Energy (BLE) (Y/N)	Does the device support BLE

Profile Codes	Which profiles? A comma-separated list of profile codes eg "A2DP, AVRCP, BIP, BPP, DUN, FTP, …"
Infrared (Y/N)	Rarely used now. Does the device support infrared capability
PC Synch (Y/N)	Can the device be connected to a PC via a cable for synchronisation of calendar/contacts
Synch ML (Y/N)	A synchronisation standard for connection campatible devices via cable, bluetooth etc
Microsoft ActiveSync (Y/N)	Microsoft's synchronisation
USB (Y/N)	Universal Serial Bus. A Yes/No field. More details are given in Connectivity Comments
USB Type-C (Y/N)	Does the device have a USB Type-C connector?
USB Version	Which version of USB does the device support?
Wi-Fi (Y/N)	Support for 802.11. A Yes/No field. More details are given in Connectivity Comments
Wi-Fi Version	Which version of Wi-Fi is supported?
802.11a (Y/N)	Does the device support this Wi-Fi standard?
802.11b (Y/N)	Does the device support this Wi-Fi standard?
802.11g (Y/N)	Does the device support this Wi-Fi standard?
802.11n (Y/N)	Does the device support this Wi-Fi standard?
802.11ac (Y/N)	Does the device support this Wi-Fi standard?
802.11ad (Y/N)	Does the device support this Wi-Fi standard?
Wi-Fi Hotspot (Y/N)	Does the device support tethering of other Wi-Fi devices such as laptops?
Wi-Fi Direct (Y/N)	Does the device support Wi-Fi connections with other compatible devices without the need for a Wi-Fi router or hub?
UMA (Y/N)	Support for Unlicensed Mobile Access
NFC	Near Field Communication
DLNA (Y/N)	Digital Living Network Alliance
HDMI (Y/N)	Does the device support HDMI?
MHL (Y/N)	Does the device support the Mobile High Definition standard for linking to HDTVs?
ANT+ (Y/N)	Does the device support ANT+
Wireless Display Support (Y/N)	Does the device support wireless data transfer to a compatible TV?
Wireless Display Standards	Which standards are supported?
Connectivity Comments	Includes other connectivity methods such as MS ActiveSync and details of micro USB or mini USB etc
Data Speed	The maximum data throughput eg 236.8 kbps
CSD (Y/N)	Circuit Switched Data. The original method of transmitting data on phones. Maximum throughput 9.6kbps

CDMA2000 1xRTT (Y/N)	Basic 3G improvement on standard CDMA2000. Enables data rates of 144 kbps
CDMA2000 1xEV-DO (Y/N)	Evolution- Data Only. Improved evolution of standard CDMA2000. Enables data rates of 2.4 Mbps
EDGE (Y/N)	Enhanced Data for Global Evolution. Also know as 2.75G.
EDGE Details	Enhanced Data for Global Evolution. Upgrade to GPRS. Includes Class and speed details where available
GPRS (Y/N)	General Packet Radio Service. Also known as 2.5G.
GPRS Details	General Packet Radio Service. Includes Class and speed details where available
HSCSD (Y/N)	High-speed circuit-switched data. Enables transfer speeds up to 38.4 kbps
HSDPA (Y/N)	Does the device support High Speed Downlink Packet Access?
HSDPA Speed	Maximum speed supported
HSUPA (Y/N)	Does the device support High Speed Uplink Packet Access?
HSUPA Speed	Maximum speed supported
HSPA+ (Y/N)	Does the device support HSPA+? HSPA+ supports data rates up to 84Mbps using MIMO, unlike LTE which uses OFDMA and MIMO.
LTE DL Speed	What is the downlink speed for LTE, if present?
LTE UL Speed	What is the uplink speed for LTE, if present?
LTE UE Category	Which LTE Cat standard does the device meet?
Max DL Speed (Mbps)	Maximum downlink speed (selected from LTE, HSPA, EDGE, GPRS and CDMA fields)
Max UL Speed (Mbps)	Maximum uplink speed (selected from LTE, HSPA, EDGE, GPRS and CDMA fields)
Data Comments	Provides more detail for the Yes/No fields
Operating System at Launch	Full details of the operating system supported at launch eg "Android vsn 4.0 Ice Cream Sandwich"
Highest OS Version Supported	What is the highest version of the operating system that is currently supported on the device?
User Interface	eg TouchWiz, S60, MOAP, UIQ
Baseband Vendor	The name of the vendor of the baseband processor eg Qualcomm, Infineon, MediaTek....
Baseband Chip	eg "Integrated in AP" or the name of the baseband chip
Apps Processor Vendor	The name of the vendor of the applications processor eg TI, NVIDIA, Samsung, Qualcomm etc
Apps Processor Chip	eg "Tegra 2", "OMAP4430" etc
GPU Vendor	Graphics Processor, eg Imagination, ARM, NVIDIA
GPU Name	Name of the GPU core, eg PowerVR SGX544 MP
Co-processor Vendor	The name of the vendor of the separate multimedia co-processor, if applicable

Co-processor Chip	The name of the co-processor chip, eg BCM2727
Processor Comments	eg “Application Processor: Marvell PXA310, 624 MHz; Base-band Processor: Qualcomm MSM6280”
Processor Speed (MHz)	Numerical value of the maximum processor speed for each CPU core
Effective Clock Speed (MHz)	A calculation based on the number of processor cores and the clock speed of each processor core. It is not a linear relationship. Dual-core effective clock spped is calculated as 1.7x clock speed of each core, while quad-core is calculated as 3x the speed of each core.
Core Count	How many CPU cores does the processor have? (doesn’t not include GPU)
Maximum Simultaneous Cores	How many of the CPU cores can be used simultaneously
Processor Architecture	32-bit or 64-bit
CPU Core	Abbreviated ARM/x86 core details
FOTA (Y/N)	Firmware over the Air
System Comments	eg “Operating System Kernel: 5.2; CPU Core: ARM11; Instruction Set: ARM v6”
JAVA	eg “CLDC-1.1, MIDP-2.0”
BREW (Y/N)	Support for Qualcomm’s BREW platform
Browser Type	eg “xHTML”, “NetFront v3.4”, “Openwave 7.2”, “Opera Mini” etc
WAP (Y/N)	Wireless Application Protocol. Allows specially-created made-for-mobile websites to be displayed on the device
WAP Version	eg “WAP 2.1”
HTML (Y/N)	HyperText Markup Language. More typical in PCs and high-end devices
WML (Y/N)	Wireless Markup Language. Old WAP standard. Typically superceded by xHTML
XML (Y/N)	eXtensible Markup Language. An umbrella standard including xHTML, RSS and SyncML.
Adobe Flash (Y/N)	Does the device run Flash Player or Flash Lite. Enables video and applications to be run on it
Adobe Flash Version	Which version of Flash Player/Flash Lite does it support?
Adobe Flash Features	Does the device support Flash for the UI, for applications, for the browser or as a web plug-in
AI Assistant (Y/N)	Does the device have an intergrated AI Assistant
AI Assistant Details	Details of onboard AI Assistant
Pre-Installed Apps/Services	Which apps/services are pre-installed on the device?
Software Comments	Additional information on any of the software fields
PIM (Y/N)	Personal Information Management. A suite of functions including alarm, calendar, organiser etc
Alarm	Alarm clock

Calculator	Self-explanatory
Calendar	Self-explanatory
Clock	12 or 24 hour clock
Currency Converter	Self-explanatory
ECML / Digital Wallet	Electronic Commerce Modeling Language. A protocol for electronic transactions
Organiser	To do list, alerts and other functions
Games (Y/N)	Does the device support standalone or online games that can be sideloaded or downloaded
Organisation Comments	Additional information on any of the organisation fields
Phonebook Capacity	Commentary on the number of contacts that can be stored in the device's memory and whether hame and email and multiple contacts can be stored
Vibrate	Does the device support vibration mode and how many types of vibration does it support
Haptic Feedback	Does the device provide vibration feedback in response to actions. Often used with touchscreens to give positive feel to touching a virtual button
GPS (Y/N)	Global Positioning by Sattelite. Used for location-based services and navigation
GPS Details	Which GPS systems are supported?
Accelerometer (Y/N)	Enables automatic switching of the display from landscape to portrait as the device is rotated
G-Sensor (Y/N)	Does the device have a gravity sensor?
Gyroscope (Y/N)	2-axis or 3-axis gyroscopes enable new game interactions and help eliminate camera shake
Magnetometer (Y/N)	Does the device detect magnetic fields?
Proximity Sensor (Y/N)	Detects whether device is near face or other object, to disable touchscreen to elimiate false screen presses
Ambient Light Sensor (Y/N)	Used to help control the backlight or screen brightness in light or dark environments
Temperature Sensor (Y/N)	Does the device support this sensor?
Humidity Sensor (Y/N)	Does the device support this sensor?
Pressure Sensor (Y/N)	Does the device support this sensor?
Heart Rate Sensor (Y/N)	Does the device support this sensor?
Fingerprint Sensor (Y/N)	Does the device support this sensor?
Gesture Sensor (Y/N)	Does the device support this sensor?
Hall Sensor (Y/N)	Does the device support this sensor?
Pico Projector (Y/N)	Small, low power projector built into the device
Flash Light (Torch)	Does the device have a built-in torch/bright light
TTY/TDD (Y/N)	Telecommunication Device for the Deaf. Allows deaf people to communicate using voice-text-voice conversion software

Misc. Comments	Additional information, includes type of GPS supported, eg A-GPS, or E911, Goggle Maps
Form Factor Group	Summary of Form Factor field, with values categorised from a list
Thickness Range	Summary of Dimensions field, with values categorised from a list
Weight Range	Summary of Weight field, with values categorised from a list
Network Group	Summary of Network field, with values categorised from a list
DL Speed Range	Summary of the 2G, 3G, 4G etc downlink data speeds
UL Speed Range	Summary of the 2G, 3G, 4G etc uplink data speeds
Battery Capacity Range	Summary of Battery Capacity field, with values categorised from a list
Standby Time Range	Summary of Standby Time field, with values categorised from a list
Talk Time Range	Summary of Talk Time field, with values categorised from a list
Display Type Group	Summary of Display Type field, with values categorised from a list
Display Size Range	Summary of Display Size field, with values categorised from a list
Display Resolution Group	Summary of Display Resolution field, with values categorised from a list
Display Colour Depth	Summary of Display Colour Depth field, with values categorised from a list
Camera Resolution Range	Summary of Camera Resolution field, with values categorised from a list
Internal Memory Group	Summary of Internal NAND Flash Memory details, with values categorised from a list
Headset Jack	Summary of Headset Jack field, with values categorised from a list
Processor Speed Range	Summary of Processor Speed field, with values categorised from a list
OS Group	Summary of Operating System field, with values categorised from a list
Manufacturer Group	Summary of Brand field, with values categorised from a list
Manufacturer's source	URL of the manufacturer's website where the specs were found

Source: Strategy Analytics, SpecTRAX Field Definitions for Criterion, *supra* note 44.

Appendix II. Specification of the Hedonic Price Model Including Only Smartphone Models Launched in 2017 or 2018

Variable	Original Specification (Missing Data Not Imputed)	Original Specification (Missing Data Imputed)	Specification Including Only Smartphone Models Launched in 2017 or 2018 (Missing Data Not Imputed)	Specification Including Only Smartphone Models Launched in 2017 or 2018 (Missing Data Imputed)
LTE-A (Y/N)	47.2348*** (18.1996)	35.3580*** (13.4942)	−4.9416 (38.6571)	21.8385 (26.8176)
TD-LTE (Y/N)	5.8623 (13.4134)	−16.4549* (9.7323)	55.3282** (22.7004)	24.8113 (19.1772)
VoWiFi (Y/N)	−45.7357** (21.8353)	−48.7108*** (15.9615)	−24.1132 (55.1742)	−7.1255 (30.9705)
Removable Battery (Y/N)	−61.0543*** (21.3383)	−39.3506*** (13.6778)	−52.2881 (65.9599)	10.0564 (31.0102)
Dual Main Camera (Y/N)	36.2012 (23.7987)	−12.0416 (15.1174)	34.2101 (45.3596)	−14.6624 (25.5063)
Primary Camera Digital Zoom	9.3950 (15.6760)	10.1908 (11.2549)	17.9807 (31.6248)	35.0037 (23.5482)
TV Out (Y/N)	78.1580*** (22.2858)	63.2184*** (15.9512)	363.4989** (166.0617)	−29.5680 (52.5146)
Handsfree	41.3436** (20.4593)	32.7294** (16.1887)	7.2161 (129.1865)	0.8703 (62.6405)
Voice Commands	142.0157*** (42.9020)	107.6537*** (27.4674)	−606.7085*** (206.8537)	−21.9027 (73.8641)
Text to Speech (Y/N)	20.7032 (29.3312)	35.0504 (21.7956)	−306.5924** (150.0589)	42.2240 (78.3960)
HD Voice (Y/N)	42.5067** (19.4181)	6.0076 (13.2886)	2.1394 (48.5989)	−6.7717 (25.9332)
Infrared (Y/N)	72.2019*** (24.0013)	89.2028*** (15.3371)	210.9904* (108.2089)	48.1506 (53.8885)
PC Synch (Y/N)	50.9499 (31.5331)	26.5866 (22.9603)	−29.9753 (109.8387)	0.9708 (63.6842)
NFC	29.1555 (20.2166)	48.1306*** (13.2500)	−22.7099 (62.3497)	68.5892** (29.2397)
DLNA (Y/N)	51.4799** (21.3224)	79.2503*** (14.4137)	137.7994 (128.0187)	118.3080*** (35.4672)
Wireless Display Support (Y/N)	−69.1538*** (14.2898)	−29.9492*** (10.5869)	−4.4445 (61.1939)	−14.3261 (49.7534)
FOTA (Y/N)	−6.1473 (32.4838)	−14.9725 (24.2898)	6.6313 (141.0069)	−3.6375 (46.7577)
HTML (Y/N)	41.5559 (40.8430)	42.8059** (18.1783)	−13.3434 (80.0733)	34.2830 (34.2496)

Haptic Feedback	−142.1532***	−97.8073***	609.1418**	42.1825
	(33.8939)	(26.7549)	(233.5137)	(90.4525)
Gyroscope (Y/N)	9.9983	16.9727	−23.8837	−27.2394
	(18.8212)	(14.2543)	(37.8332)	(26.5992)
Pressure Sensor (Y/N)	107.5538***	75.0562***	80.8349	98.7391***
	(21.6778)	(15.3628)	(61.0355)	(32.7577)
Fingerprint Sensor (Y/N)	−68.9596***	−48.7961***	−74.1396**	−17.5381
	(18.3469)	(13.0137)	(29.2174)	(25.9414)
Gesture Sensor (Y/N)	−7.4448	−18.6366	200.5631*	0.5426
	(22.6622)	(15.0004)	(101.0027)	(42.9299)
Hall Sensor (Y/N)	−67.2767***	−22.9032*	82.9245	9.5895
	(17.8832)	(11.7719)	(53.8670)	(27.5392)
TTY/TDD (Y/N)	−9.5013	−15.4429	16.2715	−67.8167**
	(17.1434)	(13.3640)	(46.2982)	(31.8843)
3G Talk Time (min)[C]	0.0273	0.0422**	−0.0009	0.0496
	(0.0243)	(0.0166)	(0.0426)	(0.0329)
Primary Video Frame Rate (fps)[C]	−0.3855	−0.3021	12.4388**	1.3530
	(0.5477)	(0.4887)	(5.6464)	(1.4570)
Battery Capacity (mAh)[C]	−0.0165	−0.0076	−0.0034	−0.0008
	(0.0189)	(0.0116)	(0.0320)	(0.0184)
Primary Display Size (Inch)[C]	84.4025***	62.0354***	110.8590***	98.8330***
	(21.6457)	(14.5608)	(38.6068)	(30.6981)
Pixels Per Inch (PPI)[C]	0.8279***	0.6372***	0.5524**	0.3249**
	(0.0924)	(0.0617)	(0.2277)	(0.1283)
Max DL Speed (Mbps)[C]	0.1243***	0.1267***	0.2202**	0.1189**
	(0.0408)	(0.0286)	(0.0999)	(0.0517)
Maximum Simultaneous Cores[C]	−5.3307	−10.5322***	−5.6815	−8.4543
	(3.3191)	(2.5330)	(10.1926)	(5.4431)
Maximum Card Size (GB)[C]	−0.0193	−0.0106	−0.0220	−0.0109
	(0.0134)	(0.0081)	(0.0379)	(0.0169)
NAND Flash (GB)				
8	−79.0918	19.1579	–	–
	(88.7711)	(47.9652)		
16	−34.3806	40.3568	62.5213	18.7062
	(89.8321)	(48.9503)	(46.6230)	(38.4149)
32	−25.9483	65.1928	87.7188	28.7499
	(91.5715)	(50.9952)	(54.9600)	(48.6027)
64	40.2973	124.0119**	91.1310	135.6436***
	(92.7905)	(52.5742)	(59.5249)	(51.8758)
128	115.9830	213.0594***	157.9163**	207.8045***
	(93.6278)	(55.2171)	(65.8534)	(60.3291)
256	222.0765**	400.8248***	244.3275***	374.1500***
	(97.1359)	(61.6583)	(66.3993)	(68.8017)
Brand				
Acer	–	−18.5965	–	–
		(107.0333)		

Alcatel	−116.8565*** (42.2436)	−46.7974 (31.6435)	−155.8665 (142.9499)	−8.0284 (72.0382)
Andy Rubin	–	237.5085** (108.3179)	–	292.6662** (130.2201)
Apple	238.3294*** (48.3873)	299.3931*** (35.1997)	–	353.1428*** (82.5854)
Asus	−70.6361 (44.6131)	−45.8635 (32.9885)	−52.3612 (145.9312)	−7.2284 (81.5061)
BlackBerry	63.3546 (44.0921)	126.8421*** (35.4504)	–	283.2096*** (106.0687)
Blackview	–	102.6413 (108.9630)	–	128.2066 (136.0497)
BLU	−120.5218*** (39.4384)	−79.5368** (31.6276)	−67.1276 (137.9509)	−36.8866 (71.0302)
Cat	19.3121 (101.8705)	213.9446*** (46.9331)	161.5419 (169.0066)	312.1984*** (97.2179)
CoolPAD	−194.5165* (101.8588)	−141.7976 (105.1390)	–	–
Doro	–	−89.4023 (106.0624)	–	–
Freetel	–	40.6799 (77.4159)	–	–
Google	82.5084 (55.9176)	165.4592*** (43.7355)	–	192.3621* (99.2054)
HP	–	225.1122** (109.8214)	–	–
Huawei	−86.7011* (51.6442)	−33.3554 (29.4363)	−135.9762 (158.7750)	−25.6786 (70.1983)
Kodak	–	264.8498** (106.2375)	–	–
Kyocera	–	44.6163 (66.9648)	–	140.7159 (135.8382)
LeEco	–	−236.9928** (106.5448)	–	–
Lenovo	23.8248 (55.4466)	−13.0224 (28.1765)	182.6693 (162.2942)	−6.0524 (67.6368)
LG	−110.9331*** (40.0316)	−42.1021* (24.7573)	−291.1562** (135.5508)	−39.5135 (65.4726)
Meitu	–	202.8408** (83.6207)	–	187.1801 (115.0202)
Meizu	–	−77.0155 (77.3097)	–	−31.0842 (127.7945)
Microsoft	−211.7718*** (60.9289)	−127.7599** (54.3493)	–	–
Motorola	−9.7006 (96.4850)	−19.5326 (38.8367)	–	–
Nokia	14.8767 (42.7481)	40.0600 (35.4345)	−77.2682 (129.9760)	−19.4067 (77.7963)

OnePlus	–	−77.9807 (50.1465)	–	−149.8576* (79.5958)
Plum	−67.8412 (97.3443)	−76.3516 (105.6096)	–	–
Razer	–	302.9332*** (107.0985)	–	302.4391** (134.2178)
Samsung	18.9959 (33.4708)	56.8683** (24.7873)	−20.0397 (115.7004)	24.7047 (71.1423)
Sky	–	−19.2090 (54.7365)	–	–
Sonim	–	436.6757*** (88.6453)	–	262.2597* (157.5930)
Sony	34.5849 (40.1189)	25.0200 (28.8311)	–	−3.0574 (65.3245)
T-Mobile	24.3087 (100.5546)	43.7713 (107.3600)	−267.4083* (159.0497)	47.3348 (131.4280)
Ulefone	–	−63.4662 (82.1075)	–	−78.9033 (126.9212)
UMI Mobiles	–	10.3359 (107.7340)	–	7.5475 (139.7411)
Verykool	−0.6711 (71.0507)	27.1279 (75.9181)	–	–
Vivo	–	−38.4103 (79.7382)	–	–
Xiaomi	−74.9723 (102.6683)	−141.0789*** (50.3046)	−236.6968 (242.1902)	−88.6644 (118.1678)
ZTE	−166.8439*** (49.9576)	−55.2414* (32.6211)	−88.7146 (132.3104)	33.3815 (77.6061)
Constant	−395.8151*** (132.8051)	−371.1475*** (76.0988)	−909.2119*** (331.6330)	−607.6591*** (146.3890)
Observations	331	711	98	262
R^2	0.9313	0.8844	0.9842	0.9123
F-Statistic	61.03	62.01	58.70	32.03
Prob > *F*	0	0	0	0
Root Mean Squared Error	83.56	100.2	57.55	103.4

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Notes: * indicates statistical significance at the 90-percent confidence level, ** indicates statistical significance at the 95-percent confidence level, and *** indicates statistical significance at the 99-percent confidence level. ^{C} indicates that the variable is continuous.

We use the *Date Launched* variable in Strategy Analytics' database to identify smartphone models that were launched in 2017 or 2018. The *Date Announced* is identical to the *Date Launched* in 63.21 percent of observations for which date information exists, and the *Date Announced* is within one month of the *Date Launched* for 88.96 percent of observations for which date information exists. Thus, we use the value of the *Date Announced* variable when the *Date Launched* variable is missing.

Appendix III. Lasso Regression Results for Smartphone Prices, Including the *Weight (gr)* Variable

Variable	Estimated Coefficient
CDMA (Y/N)	0
LTE-A (Y/N)	45.41155
TD-SCDMA (Y/N)	0
TD-LTE (Y/N)	31.44572
VoLTE (Y/N)	13.06219
VoWiFi (Y/N)	0
Ruggedized (Y/N)	0
Removable Battery (Y/N)	−79.06405
Wireless Charging (Y/N)	0
Pred Text (Y/N)	0
Dual Main Camera (Y/N)	49.64039
Primary Camera Digital Zoom	52.60044
TV Out (Y/N)	105.0254
Handsfree	86.44581
Voice Commands	157.8764
Text to Speech (Y/N)	−14.75285
HD Voice (Y/N)	−26.89681
Bluetooth Low Energy (BLE) (Y/N)	0
Infrared (Y/N)	6.870466
PC Synch (Y/N)	43.6379
Microsoft Active Sync (Y/N)	0
USB Type C (Y/N)	−25.55161
UMA (Y/N)	0
NFC	109.9462
DLNA (Y/N)	37.69178
HDMI (Y/N)	0
MHL (Y/N)	0
Wireless Display Support (Y/N)	−30.50761
FOTA (Y/N)	−36.22347
HTML (Y/N)	15.11274
AI Assistant (Y/N)	65.56574
ECML Digital Wallet	0

Organiser	0
Vibrate	0
Haptic Feedback	−121.6833
G Sensor (Y/N)	0
Gyroscope (Y/N)	33.51363
Magnetometer (Y/N)	0
Ambient Light Sensor (Y/N)	0
Pressure Sensor (Y/N)	129.7017
Fingerprint Sensor (Y/N)	−69.8438
Gesture Sensor (Y/N)	22.53068
Hall Sensor (Y/N)	−54.0455
Flash Light Torch	0
TTY/TDD (Y/N)	−21.25393
3G Talk Time (min)C	0.0468953
Primary Video Frame Rate (fps)C	−0.3275169
Battery Capacity (mAh)C	0
Primary Display Size (Inch)C	11.15155
Pixels Per Inch (PPI)C	0.7267368
Primary Camera Size (MP)	0
Max DL Speed (Mbps)C	0.2135906
Processor Speed (MHz)C	0
Maximum Simultaneous CoresC	−14.42577
Maximum Card Size (GB)C	−0.0397386
RAM (MB)C	0
Weight (gr)C	0
Constant	−196.535
Observations	307
R^2	0.8616
alpha	1.0000
lambda	1.3732
Cross-Validation Mean Squared Error	13111.7764

Source: Strategy Analytics, SpecTRAX Service, supra note 2, tab 2 ("Device Specifications").

Appendix IV. Hedonic Price Regression Results for Smartphone Launch Prices, Including the *Weight (gr)* Variable

Variable	Regression Based on Nonimputed Data	Regression Based on Imputed Data
LTE-A (Y/N)	47.5240** (18.4910)	35.5997*** (13.4759)
TD-LTE (Y/N)	6.6179 (13.5875)	−17.5468* (9.7404)
VoWiFi (Y/N)	−43.8077** (22.2234)	−52.1344*** (16.0697)
Removable Battery (Y/N)	−61.6488*** (22.9080)	−37.0906*** (13.7251)
Dual Main Camera (Y/N)	35.5369 (24.0075)	−9.9768 (15.1464)
Primary Camera Digital Zoom	17.2687 (16.5166)	9.8246 (11.2411)
TV Out (Y/N)	80.2433*** (22.7750)	60.8210*** (15.9930)
Handsfree	42.8188* (22.3854)	35.2869** (16.2379)
Voice Commands	135.3656*** (44.0337)	107.3911*** (27.4289)
Text to Speech (Y/N)	17.1090 (29.7926)	37.4141* (21.8105)
HD Voice (Y/N)	39.1123* (19.9128)	6.3741 (13.2716)
Infrared (Y/N)	71.7715*** (24.6484)	88.5282*** (15.3207)
PC Synch (Y/N)	55.5652* (32.0233)	28.1288 (22.9463)
NFC	24.5290 (20.9743)	49.6741*** (13.2634)
DLNA (Y/N)	58.5897*** (22.3079)	79.3735*** (14.3934)
Wireless Display Support (Y/N)	−69.2452*** (14.5360)	−30.9070*** (10.5874)
FOTA (Y/N)	−7.3514 (32.9585)	−14.9533 (24.2553)

HTML (Y/N)		42.2111	42.7668**
		(42.6571)	(18.1526)
Haptic Feedback		−137.7014***	−100.1827***
		(36.4553)	(26.7547)
Gyroscope (Y/N)		0.5357	16.1951
		(19.7390)	(14.2417)
Pressure Sensor (Y/N)		111.2471***	75.6274***
		(22.1523)	(15.3448)
Fingerprint Sensor (Y/N)		−74.9481***	−47.2131***
		(19.0690)	(13.0296)
Gesture Sensor (Y/N)		−8.0492	−18.6141
		(22.9587)	(14.9791)
Hall Sensor (Y/N)		−60.7487***	−24.3087**
		(19.1958)	(11.7852)
TTY/TDD (Y/N)		−8.0442	−15.7054
		(17.3590)	(13.3459)
3G Talk Time (min)[C]		0.0132	0.0424**
		(0.0258)	(0.0165)
Primary Video Frame Rate (fps)[C]		−0.3332	−0.3331
		(0.5565)	(0.4884)
Battery Capacity (mAh)[C]		0.0030	−0.0006
		(0.0230)	(0.0123)
Primary Display Size (Inch)[C]		87.3292***	76.0097***
		(29.1319)	(16.7701)
Pixels Per Inch (PPI)[C]		0.8402***	0.6363***
		(0.0971)	(0.0616)
Max DL Speed (Mbps)[C]		0.1275***	0.1295***
		(0.0414)	(0.0286)
Maximum Simultaneous Cores[C]		−5.9053*	−10.6757***
		(3.3877)	(2.5309)
Maximum Card Size (GB)[C]		−0.0180	−0.0130
		(0.0136)	(0.0082)
Weight (gr)[C]		−0.3292	−0.5103*
		(0.5178)	(0.3051)
NAND Flash (GB)			
	8	−77.3729	11.6939
		(89.5857)	(48.1046)
	16	−39.3589	29.1505
		(91.2496)	(49.3380)
	32	−31.2055	54.3191
		(92.9702)	(51.3362)

64	35.8375 (94.1964)	113.7240** (52.8588)
128	110.6242 (95.0753)	200.3264*** (55.6619)
256	217.7432** (98.4990)	389.1736*** (61.9637)
Brand		
Acer	–	−42.8464 (107.8605)
Alcatel	−104.1213** (46.5815)	−48.8624 (31.6227)
Andy Rubin	–	234.0782** (108.1837)
Apple	249.2339*** (49.4287)	304.3509*** (35.2745)
Asus	−75.5285 (46.4800)	−53.4039 (33.2488)
BlackBerry	63.5084 (45.1003)	135.9973*** (35.8208)
Blackview	–	87.4812 (109.1853)
BLU	−123.7089*** (40.2977)	−85.0462*** (31.7541)
Cat	13.7588 (107.3866)	221.9520*** (47.1105)
CoolPAD	−185.3280* (103.1127)	−142.6694 (104.9912)
Doro	–	−89.0093 (105.9122)
Freetel	–	29.3542 (77.6021)
Google	81.8782 (57.5975)	156.7578*** (43.9822)
HP	–	219.7090** (109.7132)
Huawei	−89.0189* (53.6101)	−42.9718 (29.9516)
Kodak	–	261.8996** (106.1015)
Kyocera	–	82.9857 (70.6960)

LeEco	–	−248.2841**
		(106.6076)
Lenovo	31.7483	−19.1497
	(57.0719)	(28.3740)
LG	−123.5368***	−52.5216**
	(44.3051)	(25.4951)
Meitu	–	199.8063**
		(83.5217)
Meizu	–	−80.4898
		(77.2280)
Microsoft	−218.9511***	−141.9097**
	(65.0889)	(54.9277)
Motorola	−8.0596	−21.6762
	(97.3389)	(38.8028)
Nokia	37.1652	39.1750
	(46.5666)	(35.3882)
OnePlus	–	−92.9567*
		(50.8697)
Plum	−48.8277	−75.0090
	(99.2728)	(105.4628)
Razer	–	304.7211***
		(106.9519)
Samsung	15.8414	49.0094*
	(35.0307)	(25.1943)
Sky	–	−20.5210
		(54.6645)
Sonim	–	509.0322***
		(98.5268)
Sony	26.5358	25.8100
	(40.7707)	(28.7941)
T-Mobile	8.1881	39.1162
	(102.0020)	(107.2438)
Ulefone	–	−69.8958
		(82.0811)
UMI Mobiles	–	7.1668
		(107.5978)
Verykool	0.6077	28.5313
	(71.9192)	(75.8150)
Vivo	–	−51.7480
		(80.0235)
Xiaomi	−71.1808	−149.7318***
	(105.1334)	(50.4989)

ZTE	−165.1526***	−57.5384*
	(50.5842)	(32.6038)
Constant	−396.5581***	−366.8692***
	(138.5618)	(76.0339)
Observations	325	711
R^2	0.9307	0.8849
F-Statistic	57.86	61.43
Prob > F	0	0
Root Mean Squared Error	84.11	100

Source: Strategy Analytics, SpecTRAX Service, supra note 2, tab 2 ("Device Specifications").

Notes: * indicates statistical significance at the 90-percent confidence level, ** indicates statistical significance at the 95-percent confidence level, and *** indicates statistical significance at the 99-percent confidence level. ^{C} indicates that the variable is continuous.

Appendix V. Univariate Regression of Smartphone Prices on the *NAND Flash (GB)* Categorical Variable

Variable		
NAND Flash (GB)		
	8	45.88662 (93.55729)
	16	181.1446** (91.78033)
	32	366.9685*** (91.79418)
	64	503.7056*** (92.40534)
	128	690.5149*** (97.0307)
	256	950.8138*** (106.8016)
Constant		119.8 (90.76391)
Observations		711
R^2		0.4716
F-Statistic		104.72
Prob > *F*		0
Root Mean Squared Error		202.95

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Notes: * indicates statistical significance at the 90-percent confidence level, ** indicates statistical significance at the 95-percent confidence level, and *** indicates statistical significance at the 99-percent confidence level.

Appendix VI. Specification of the Hedonic Price Model Excluding the *NAND Flash (GB)* Categorical Variable

Variable	
LTE-A (Y/N)	38.7243* (20.1328)
TD-LTE (Y/N)	4.8950 (15.0274)
VoWiFi (Y/N)	−45.2144* (24.6067)
Removable Battery (Y/N)	−61.1528** (23.5849)
Dual Main Camera (Y/N)	41.1061 (26.4569)
Primary Camera Digital Zoom	11.0668 (17.5674)
TV Out (Y/N)	50.2067** (24.7725)
Handsfree	58.5979** (22.7931)
Voice Commands	149.5389*** (47.4446)
Text to Speech (Y/N)	19.8428 (33.0212)
HD Voice (Y/N)	38.2611* (21.5556)
Infrared (Y/N)	80.3819*** (26.9881)
PC Synch (Y/N)	49.6163 (35.1287)
NFC	41.3348* (22.1423)
DLNA (Y/N)	44.8773* (23.8385)
Wireless Display Support (Y/N)	−69.0992*** (16.0420)
FOTA (Y/N)	−5.5393 (36.1904)
HTML (Y/N)	43.3669 (45.7058)

Haptic Feedback	−138.3107***
	(37.4739)
Gyroscope (Y/N)	29.8376
	(20.4530)
Pressure Sensor (Y/N)	90.3522***
	(23.8366)
Fingerprint Sensor (Y/N)	−60.4428***
	(20.3295)
Gesture Sensor (Y/N)	−7.2004
	(25.3765)
Hall Sensor (Y/N)	−80.5150***
	(19.9783)
TTY/TDD (Y/N)	−12.8329
	(19.1388)
3G Talk Time (min)^{C}	0.0246
	(0.0274)
Primary Video Frame Rate (fps)^{C}	−0.3403
	(0.6147)
Battery Capacity (mAh)^{C}	−0.0175
	(0.0212)
Primary Display Size (Inch)^{C}	91.4744***
	(24.0311)
Pixels Per Inch (PPI)^{C}	0.8619***
	(0.1005)
Max DL Speed (Mbps)^{C}	0.2444***
	(0.0422)
Maximum Simultaneous Cores^{C}	−3.8845
	(3.6454)
Maximum Card Size (GB)^{C}	−0.0233
	(0.0150)
Brand	
Acer	–
Alcatel	−115.3842**
	(47.4493)
Andy Rubin	–
Apple	305.1223***
	(53.5397)
Asus	−75.2028
	(50.1692)
BlackBerry	70.6593
	(49.4647)

Blackview	–
BLU	–104.2036**
	(44.0376)
Cat	33.1899
	(114.4806)
CoolPAD	–160.3568
	(113.1752)
Doro	–
Freetel	–
Google	132.6176**
	(61.6571)
HP	–
Huawei	–67.5153
	(57.3077)
Kodak	–
Kyocera	–
LeEco	–
Lenovo	52.8673
	(61.5146)
LG	–110.8442**
	(45.0274)
Meitu	–
Meizu	–
Microsoft	–227.0734***
	(68.5431)
Motorola	–12.3485
	(108.7557)
Nokia	13.5195
	(48.0673)
OnePlus	–
Plum	–89.6179
	(109.0848)
Razer	–
Samsung	21.8901
	(37.6970)
Sky	–
Sonim	–
Sony	56.9603
	(45.0502)

	T-Mobile	46.4459 (112.6707)
	Ulefone	–
	UMI Mobiles	–
	Verykool	–13.5076 (79.2937)
	Vivo	–
	Xiaomi	–77.7604 (115.3613)
	ZTE	–156.7000*** (56.2376)
Constant		–531.7111*** (121.2947)
Observations		331
R^2		0.9107
F-Statistic		52.13
Prob > F		0
Root Mean Squared Error		94.25

Source: Strategy Analytics, SpecTRAX Service, *supra* note 2, tab 2 ("Device Specifications").
Notes: * indicates statistical significance at the 90-percent confidence level, ** indicates statistical significance at the 95-percent confidence level, and *** indicates statistical significance at the 99-percent confidence level. ^{C} indicates that the variable is continuous.