The Dynamics of Technology Adoption and Vertical Restraints: An Empirical Analysis

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October 2016

Preliminary and Incomplete

Abstract

This paper studies the impact of vertical restraints in the x86 processor industry, where a dominant upstream supplier (Intel) competes with a smaller contender, Advanced Micro Devices (AMD). During the studied period, Intel's strategy included a controversial program, "Intel Inside," through which it offered downstream clients rebates and subsidies that were conditioned on the volume purchased from it and, sometimes, on the volume purchased from AMD. We document the manner by which such restraints interact with the dynamic process of downstream technology adoption. Our preliminary results indicate, first, that Intel's restraints were binding: restrictions imposed on a downstream client reduced the rate of its AMD adoption. They also illustrate the role played by dynamics and downstream clients' expectations: we find that (i) adoption of the AMD technology by a given downstream firm was negatively affected by restrictions imposed on other downstream firms, and that (ii) adoption was an increasing function of the intensity of antitrust litigation against Intel.

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1 Introduction

> "There is perhaps no aspect of competition policy that is as controversial or has been as inconsistent over time and across jurisdictions as policy towards restraints between upstream firms and their downstream retailers" Lafontaine and Slade (2008)

Upstream manufacturers often impose exclusive dealing contracts on their retailers, which may result in foreclosure of a competing brand. On the other hand, there may be procompetitive effects of exclusive dealing. For example, exclusivity could enhance market performance by inducing a retailer to focus its promotional activities on the manufacturer's products and thereby enhance the provision of customers' service. It could also secure investments made by the manufacturer (such as quality assurance and advertising) by preventing the retailer from "free-riding" on these investments.[2] Due to its potential procompetitive effects, the *per se* illegality characterization of exclusive dealing was rejected in Standard Oil Co. v. United States (Standard Stations), 337 U.S. 293, 305 -06 (1949) and the US courts treat exclusive dealing under the "rule of reason" legality rule.[3] Motivated by these conflicting aspects of exclusive dealing contracts, a vast theoretical and empirical literature has sought to identify their impact given various market conditions.

One of the challenging tasks within this research agenda has been to empirically identify the foreclosure effect, i.e., the impact of vertical restraints imposed by one upstream firm on the sales of a competing upstream firm. An example of such work is Ater's (2015) documentation of the negative effect of exclusive dealings on upstream rivals' market shares in the fast-food industry. In general, empirical evidence on this issue is scarce. Our paper contributes to this literature while emphasizing an aspect that has not been addressed to date, to the best of our knowledge: the effect of vertical restraints on the dynamics of downstream technology adoption.

[2] Marvel (1982) and Besanko and Perry (1993) provide more discussion of this issue.

[3] Potential pro- and anti-competitive effects of exclusive dealing and the history of its legal statues in the US are discussed in Areeda and Kaplow (1997) and Sullivan and Hovenkamp (2003). Exclusive dealing may violate the Clayton Act (Section 3) and the Sherman Act (Section 2). The rule of reason approach was reaffirmed in Tampa Elec. Co. v. Nashville Coal Co., 365 U.S. 320 (1961)

Consider an upstream industry that sells critical components to downstream customers. The upstream industry features a dominant incumbent firm, and a smaller entrant, whose stated goal is to challenge the dominant position of the incumbent. Suppose further that this upstream industry is characterized by rapid innovation, large sunk investments, and capacity constraints. Downstream customers, for their part, crucially depend on timely shipments from the upstream industry. In this setup, exclusive dealing contracts with major downstream clients may curb the downstream adoption of the rival's technology, effectively inhibiting its growth. Being excluded from selling to the major downstream customers, the smaller upstream supplier may struggle to expand its customer base and production volumes. This, in turn, may limit its ability to finance investments in Research and Development (R&D) and capacity expansion, perpetuating its inferior position. This mechanism is likely to be taken into account by downstream customers and may affect their expectations regarding the smaller competitor's ability to deliver timely and reliable shipments, lowering the perceived long-run benefits from adopting its technology.

This paper estimates dynamic panel models that document such patterns in the semiconductor industry. Specifically, we study competition in the microprocessor x86 market between Intel, traditionally controlling about 80% of the market, and its rival AMD that controls much of the remaining 20% market share. Our analysis covers the years 2002-2009 and focuses on the role played by the "Intel Inside" program. Mostly throughout 2002-2005, this program funneled substantial payments from Intel to its downstream clients, i.e., PC manufacturers such as Dell, HP and Toshiba, in the form of rebates and advertising subsidies. As revealed in court cases and regulatory investigations, such payments were sometimes explicitly conditioned on the extent of the client's purchases from Intel's rival, AMD (see Lee, Pechy and Sovinsky 2013, hereafter LPS). Intel's arrangement with HP, for example, specified that the share of HP's business line PCs using AMD's chips was not to exceed 5%, while manufacturers such as Dell and Toshiba refrained from using AMD's chips altogether.

The Intel Inside program illustrates the basic dilemma faced by regulators with respect to exclusive dealings. On the one hand, excluding AMD from downstream manufacturers' product lines clearly raises anticompetitive concerns. On the other hand, the program may have had procompetitive aspects: it provided downstream manufacturers with incentives to focus their entire production process on Intel's technology, possibly creating economies of scale with some of the efficiency gains being passed to consumers. Fierce downstream competition may have, indeed, allowed consumers to enjoy a substantial share of such efficiency gains, and rebates on CPU purchases may have similarly ended up benefitting consumers. This program may have also facilitated Intel's ability to capitalize on its investments, thus promoting innovation. Nonetheless, LPS find evidence that the advertising subsidies received by some of Intel's large customers (notably Dell) were *predatory* in the sense that their magnitude appeared inconsistent with profit maximization. The controversial nature of the program was manifested in a series of complaints and lawsuits filed by AMD with antitrust authorities and courts worldwide, leading to active investigations and lawsuits filed by regulators. This process gained strong traction in the years 2004-2006. Ultimately, the bulk of these legal proceedings were settled, with Intel agreeing to roll back the controversial aspects of this program.

Ideally, empirical work should attempt to measure both the social benefits and the social costs of the Intel Inside program. Our goal in this paper, however, is different: we are interested in documenting the impact of upstream vertical restraints on the downstream adoption of a rival's technology within a dynamic environment.

Our empirical analysis combines several datasets. We document the downstream adoption of AMD's technology using market level data on PC brands' prices, characteristics and sales, indicating the share of PCs that had an AMD chip installed for each PC brand over time. We also collected data on the evolution of the upstream firms' technology and capacity. We draw on court cases and additional sources to construct variables that describe various aspects of the Intel Inside program, such as the volume of payments made to individual downstream clients, and specific restrictions dictated by Intel on their use of the AMD technology. Finally, we construct indices capturing the extent of litigation mounted by AMD and competition authorities worldwide in connection with the Intel Inside program. The joint variation of such variables over time allows us to identify the dynamic impact of technology, vertical restraints, and litigation, on the downstream adoption of AMD's technology. Sharp variation in some of these measures, such as Intel's decision to role back much of the controversial aspects of its Intel Inside program midway through the sample period, is very helpful in separately identifying these effects.

We estimate linear and nonlinear dynamic panel models in which the unit of observation is an individual downstream product line by market segment (e.g., HP's "Pavilion" desktop for the home market), and where the dependent variable is the share of this product line's sales that have an AMD chip installed. The remaining variables serve as explanatory variables. Our preliminary results display the following patterns: the adoption of AMD's technology by a given downstream customer responds negatively to (i) the extent of payments via "Intel Inside" to the downstream customer itself, (ii) specific restrictions on the extent of usage of AMD's technology imposed on the customer by the Intel Inside arrangement, (iii) a measure of Intel's technology performance, and (iv) restrictions imposed on other customers. We further find that the extent of adoption responds positively to (i) a measure of the AMD technology performance (ii) a measure of AMD's production capacity, and (iii) the extent of "anti-Intel Inside" litigation.

We interpret these findings as reflecting the importance of dynamics in the technology adoption process. Institutional details suggest that this decision is inherently dynamic. First, as is typical with technology adoption, the extent of current adoption affects the future costs of using the technology. For example, when a downstream PC maker sets up, or expands, a production line that is especially suited for AMD-based PCs, it may reduce its cost of using the AMD technology in both current and future periods. Other dynamic considerations have to do with the fact that the extent of current adoption of the AMD technology may affect both current and future benefits from the "Intel Inside" program. Ultimately, downstream customers need to weigh the potential benefits from adopting AMD's technology against its costs, and evaluation of both the benefits and the costs crucially depends on firm's expectations regarding several strategic variables: AMD's production capacity and technological progress contrasted with that of Intel, and the future viability of Intel's vertical restraints.

Specifically, if downstream clients believe that the restraints would likely be lifted on account of mounting regulatory pressure on Intel, they may revise their beliefs regarding both the future costs and the future benefits of adopting the AMD technology, resulting in increased adoption. Moreover, if the restraints affect AMD's cashflow and its ability to invest in capacity expansion, it is possible that by controlling for AMD's capacity, we underestimate the impact of these restraints. Indeed, when we remove the capacity variables from the analysis, we find stronger vertical restraints effects of the adoption of AMD.

The response of a client's adoption decisions to restrictions imposed on other clients is noteworthy: although the exact contracts signed between Intel and a specific downstream client were not common knowledge at the time they were made, other clients may have had some information about them. For example, firms could easily observe the quantity of PCs with AMD processors sold by other firms, where this quantity was zero for major market players over many periods. If a client concludes or observes (albeit imperfectly) that other firms accept substantial restrictions on their adoption of the AMD technology, they may revise downwards their expectations regarding AMD's future market position, investment and performance. What we document is, therefore, an interesting aspect of the dynamic and subtle effect of exclusive contracts on the downstream adoption of the rival technology. Indeed, our results indicate that exclusive restrictions had an impact on AMD adoption by all firms, not only those that were a party to the exclusive arrangement with Intel.

The rest of the paper is organized as follows. After a brief literature review, section 2 describes the data sources we draw on. Section 3 explains our empirical strategy, i.e., the applicability of dynamic panel models to the question at hand. Section 4 provides our preliminary results, and section 5 concludes with some discussion of limitations and future research.

Related literature. Our paper belongs in a small but growing empirical literature on exclusive dealing and vertical contracts (see Lafontaine and Slade 2008 for an overview). Asker (forthcoming) examines the Chicago beer market and uses an indirect approach to measure the effect of exclusive dealing on entry. He finds that rivals do not have higher costs when they must compete with firms who sell under exclusive dealing agreements, in contrast to a raising-rivals'-cost view of exclusive dealings. Sass (2005) also studies the beer market and finds that exclusive dealing is more prevalent in smaller markets, in contrast to the predictions of foreclosure theory models. Nurski and Verboven (2016) estimate a structural model of demand with product and spatial differentiation and dealer exclusivity applied to the automobile market, assess the anti-competitive profit incentives for exclusive dealing, and subsequently evaluate the impact on consumers and welfare. They find that exclusive dealing in the European car market has served as a mild barrier to entry against Asian competitors, but with considerable consequences on consumers' domestic welfare because of reduced spatial coverage.

Our paper is closest to Ater (2015) who empirically quantifies the effect of exclusive dealing contracts on sales in the fast food industry. He finds that exclusive dealing reduces sales, and concludes that this is inconsistent with efficiencies, so that exclusive dealing must be used for anti-competitive reasons. Our paper contributes to this line of research by considering a technology market where an interesting and complex dynamic relationship arises between exclusive dealings, downstream technology adoption, and upstream innovation and capacity investments.[4]

Our paper is also related to a large literature on the PC and CPU industries. Several papers study the nature of innovation in the x86 microprocessor industry. Some examples that rely on static structural models include Song (2007), who uses the pure characteristics demand model to quantify the benefits from such innovation, and Eizenberg (2014), who studies the impact of CPU innovation on the variety of downstream PC configurations. Gordon (2009) uses a dynamic demand model to study consumer replacement cycles, and Goettler and Gordon (2011) estimate a dynamic model in which innovation by Intel and AMD is endogenously determined, and use it to predict the impact of innovation from a hypothetical exclusion of AMD from the market. Our work differs from these papers by studying the dynamic adoption process of the AMD technology by downstream PC makers. Our empirical approach relies on dynamic panel methods rather than on structural modeling, which has both benefits and costs: while the lack of a dynamic structural model limits our ability to analyze out-of-sample scenarios, it allows us to avoid some of the strong assumptions required in the estimation of dynamic games. In particular, we are able to perform estimation on a dataset with rich and detailed product-level data without running into large state space concerns.

A closely related paper is LPS that uses a structural approach to estimate the marginal

[4] Additional contributions include Slade (2000) and Suzuki (2009).

benefit to Intel from a dollar invested in the "Intel Inside" program. As this marginal benefit appears substantially lower than the marginal cost, LPS conclude that the subsidizing of advertising via this program has been predatory in nature, and was meant to exclude AMD. While LPS examines the Intel Inside program, they do not consider PC firms' product-line choices, focusing instead on Intel's advertising decisions. The current paper, by contrast, explicitly addresses product-line choices: we document the effect of vertical restraints on the downstream technology adoption process, emphasizing its dynamic nature.

Finally, a vast theoretical literature provides motivation for pro as well as anticompetitive views of exclusive contracts and other vertical restraints. Exclusive dealing was initially considered an anticompetitive barrier to entry. However, the Chicago critique maintained that an exclusive deal is not in the joint interest of the upstream and downstream firm, thereby dismissing the view that exclusive contracts could be used to exclude a rival and enhance market power.[5]

The post-Chicago theoretical literature, in contrast, has identified conditions under which socially harmful exclusive contracts may arise. These are situations in which an incumbent and a retailer may have a joint incentive to contract on exclusive dealing as a means of foreclosing entry. The main insight is that such contracts imply externalities on other players not accounted for in the Chicago-critique. Spector (2011) finds that if contracts are required to be simple enough, this strategy may induce inefficient exclusion even if the excluded firm is present at the contracting stage. Exclusive contracts may thus cause inefficient eviction, not only entry-deterrence, even though the former is less likely than the latter. Yehezkel (2008) considers the relationship between vertical contracts and product variety, and focuses on the

[5] First, if offering a second brand increases the retailer's profit, then the manufacturer can charge the retailer higher franchise fees. Therefore, if a manufacturer finds it profitable to foreclose a competing brand then it has to be that this brand is not profitable to begin with. Second, if for whatever reason a manufacturer wishes to foreclose a competing brand, then the manufacturer can choose between imposing exclusive dealing on the retailer, or offering him quantity discounts to induce the retailer to choose not to carry the competing brand. Either way, the manufacturer needs to compensate the retailer for the foregone profits from offering the competing brand. Thus it is not clear why exclusive dealing is any better from the manufacturer's viewpoint than quantity discounts that are less open to antitrust scrutiny. Third, the fact that the retailer has the option to carry the competing brand will force the manufacturer to offer discounts that the retailer is likely to pass on, at least partially, to consumers. In that sense, the competitive pressure from the competing brand holds even in the presence of exclusive dealing. As Gilbert (2000) points out, the arguments made by the "Chicago School" parallels a more tolerant approach by US courts towards exclusive dealing.

case where a dominant manufacturer prohibits its retailer from selling products that compete with its own, and finds that quality choices by downstream retailers depend crucially on the extent to which the retailer is privately informed about consumers' average willingness to pay. Under full information, the retailer offers both quality varieties only if it is optimal to do so under vertical integration. However, when the retailer is privately informed about demand, it offers both varieties even if under vertical integration it is profitable to offer only the manufacturer's product. If the manufacturer can impose exclusive dealing, it will do so and foreclose the low quality substitute even if under vertical integration it is profitable to offer both varieties.[6]

2 Data

We use data from several sources, containing information on PC and CPU sales and attributes, PC firms' advertising expenditures, measures of processor quality, AMD and Intel's production capacity, and the evolution of their technology. In addition, we use information on the nature of the vertical restraints Intel imposed on downstream PC firms, and the extent to which legal action has been taken against Intel related to their vertical restraints as noted in court cases.

2.1 Sales, Attributes and Advertising

We use quarterly data on PC sales in the US home and business sectors available from the Gartner Group, covering the years 2002-2009.[7] A unit of observation is defined as a combination of PC vendor (e.g., Dell), PC vendor brand (e.g., Inspiron), market segment (e.g., Home), CPU vendor (e.g., Intel), CPU family (e.g., Pentium 4) and quarter. We focus our analysis on the home and business segments.[8] We exclude Apple products as those

[6] For related theoretical contributiuons, see for example Inderst and Shaffer (2007) and Lommerud, Straume and Stogard (2003).

[7] We do not include servers as server sales were not recorded in the Gartner dataset prior to 2005.

[8] All variables expressed in monetary terms were deflated using the quarterly consumer price index of the Bureau of Labor Statistics, basis set at the year 2000 USD.

exclusively used IBM's chips for much of the sample period, utilizing Intel's chips afterwards. We obtain data on worldwide CPU sales from various web sources.[9]

	Obs	Mean	Std. Dev.	Min	Max
Percentage AMD Sold	3508	0.13	0.25	0	1
PC Characteristics					
Price PC (1000$)	3508	1.02	0.45	0.24	3.69
Brand Advertising (M$)	3508	1.01	3.10	0.00	29.14
Firm Advertising (M$)	3508	8.16	16.46	0.00	87.80
CPU Characteristics					
AMD CPU benchmark/dollar, if non-zero	1234	7.31	4.54	1.75	22.65
Intel CPU benchmark/dollar, if non-zero	3349	4.69	3.85	0.84	32.66
Quarters Brand/AMD family available, if non-zero	1234	5.42	3.20	1	19
Quarters Brand/Intel family available, if non-zero	3349	6.42	3.76	1	30
Capacity Related Variables					
Free Cash (100M$)	3508	8.31	3.12	3.97	19.05
AMD Capacity Index	3508	8.08	3.59	3	13
Intel Capacity Index	3508	31.93	6.71	23	44
Exclusionary Restriction/Antitrust Related Variables					
Exclusionary Restriction Index	3508	1.03	2.03	0	6
Intel Payments to Dell (M$)	3508	147.38	154.15	13.37	603.05
Intel Payments to each PC Firm (M$)	3508	36.83	95.24	0.00	603.05
Cumulative Antitrust Cases Against Intel	3508	4.19	2.15	1	7
Pending Antitrust Cases Against Intel	3508	3.45	1.62	1	6

Table 1: Descriptive Statistics (PC Brand Segment Quarter Level)

Table 1 shows descriptive statistics at the PC brand-segment-quarter level. The total number of observations is 3,508. As the table indicates, the rate of utilization of AMD's chips is on average 13%. The PC characteristics show significant variation as the average price of a brand ranges from $240 to $3,690. We also create a variable to account for how long a PC brand has been available equipped with AMD chips (resp. Intel), counting the number of quarters. If a PC brand was never equipped with AMD (resp. Intel), the variable is set to zero. As can be seen in Table 1, the average number of quarters these combinations are available is one unit bigger for Intel than for AMD-based machines (conditional on the brand-segment offering at least one of the CPU manufacturer's products). These numbers confirm that Intel has an incumbency advantage.

[9] Sources are: wikipedia.com, businesswire.com

The evolution of the principal variable, the market share of AMD, is shown in Figure 1 (overall market share across PC brands and segments, the remaining share garnered by Intel). The rise in market share during the year 2006 from 10% to 20% is of interest. It seems indeed to be closely timed with a loosening of the restrictions of the Intel Inside program (which we discuss below and illustrate in Figure 5). The gain in market share is however not maintained over time as it declines after 2008 to reach 12.5% in 2009. Our framework would attempt to explain this variation.

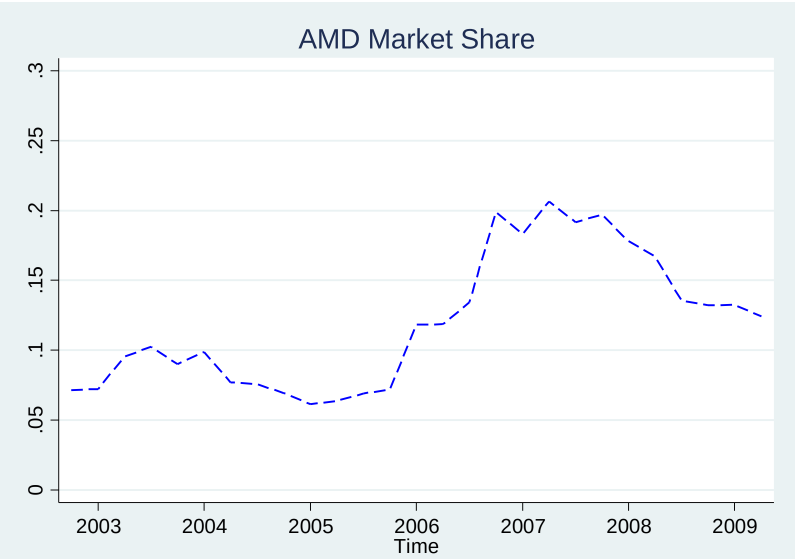

Figure 1: AMD Market Shares

Figure 2 provides more details about the evolution of AMD's market share: it shows AMD market share within selected PC firms (the remainder being Intel's market share) and the share of these PC firms in the market. We compute mean market shares over quarters for two different periods: before and after the first quarter of 2006, when most major restrictions were stopped by Intel. The figure reveals that the increase in AMD's market share did not only come from those PC firms that were directly subject to Intel's exclusionary restrictions: for example, AMD's adoption by Gateway went up considerably.

PC advertisement data come from the Kantar Media Group. These data are important because many rebates given by Intel were a function of advertising done by PC firms. These consist of PC brand-specific ad expenditures (e.g. Acer Aspire) and PC firm level ad ex-

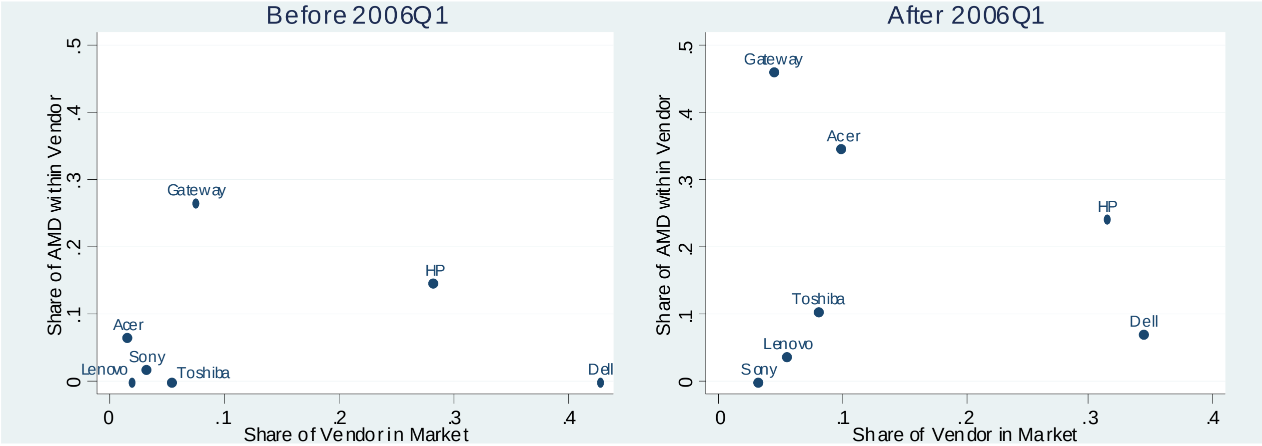

Figure 2: PC Vendor Specific Market Shares

penditures (e.g. Acer) where we match sales and advertising data across brands.[10] Table 1 shows that expenditures for brand-specific ads averaged \$1 million while firm-specific expenditures averaged \$8.2 million (the observed maximum of \$87 million was due to exceptionally large expenditures on TV advertisements).

2.2 CPU Quality

We obtain data on the quality of the CPU from Passmark's CPU Mark publications.[11] This company collects measurements on CPU tests from users around the world, and creates a database of CPU performance at the CPU model level. It provides a benchmark score: a continuous measure of performance for each CPU model. These contain a continuous quality measure ("benchmark") for each CPU model. We use this together with CPU prices, which we gathered from published list prices or obtained from Instat, to construct a benchmark per dollar spent index.[12] Complete details regarding the construction of those series are provided in the Appendix.

The descriptive statistics proposed in Table 1 are computed on the non-zero observations

[10] For a few PC firms, the Kantar brands were available at a more aggregate level than the Gartner sales data. Thus, the match occurred at the Kantar brand level.

[11] www.cpubenchmark.net

[12] Instat "Intel Rosetta Stone: Intel Processor Shipments, Forecasts, Technology and Roadmaps" November 2005.

only in order to allow a meaningful comparison of the two variables since a PC brand without any AMD CPUs will always have a zero value for its AMD quality measure. We see that AMD CPUs have on average almost 35% better benchmark per dollar than Intel CPUs. Moreover, Figure 3 shows the evolution over time of the sales weighted average of the benchmark per dollar measure for both firms. As can be seen, AMD's quality measure was consistently better than Intel's throughout the sample, both due to lower AMD prices and higher AMD benchmark values.

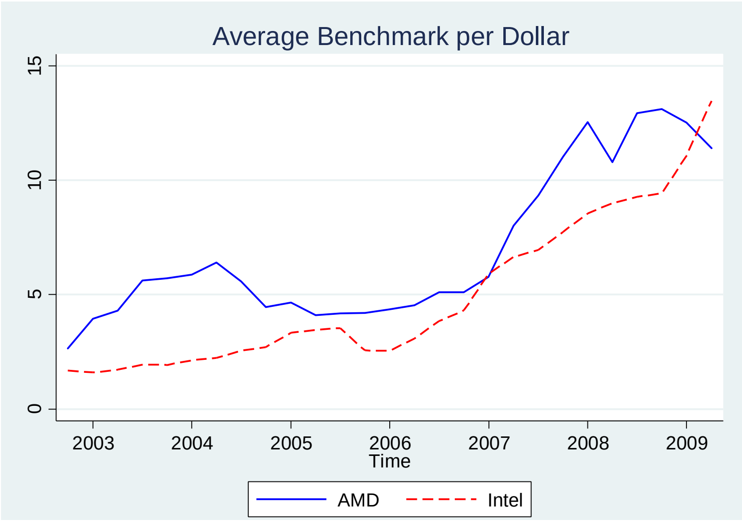

Figure 3: CPU Quality Per Dollar

2.3 CPU Production Technology and Capacity

To account for production technology/total capacity of the CPU manufacturers, we use information from Intel and AMD annual reports. For each year, these report: the number of fabrication units available for making microprocessors (FABs), the silicon wafer size of each FAB (the larger the wafer, the more CPUs can be printed simultaneously), and the precision in nanometers available at each FAB for "printing" the integrated circuits (the smaller the precision, the more CPUs can be printed, moreover the CPU power efficiency is improved). We construct a measure of output/quality of the technology process of Intel (respectively AMD), the capacity index, as the sum over all FABs of (ordered) wafer size and (ordered) IC process. We also construct a measure of AMD's "cash flow available" for investing at the beginning of each quarter (from SEC quarterly reports).[13] Table 1 reveals that the Free Cash available for AMD in each quarter is on average $831 million and that the mean capacity index of Intel is on average 4 times larger than AMD's.

Table 2 shows the evolution of the CPU manufacturers' production technology and capacity over time. AMD usually lags behind Intel regarding the IC process and the wafer size. The variation in Intel's number of FABs is due to technological upgrades and relocations. As can be seen, our capacity index captures these variations, and demonstrates Intel's established advantage in production technology and capacity.

Year	Number of Fabs		Mean ICP in nm		Mean wafer in mm		Capacity index	
	AMD	Intel	AMD	Intel	AMD	Intel	AMD	Intel
2002	1	10	130	150	200	220	3	28
2003	1	7	130	130	200	229	3	23
2004	1	7	130	113	200	243	3	27
2005	2	6	90	78	250	300	9	33
2006	2	5	90	75	250	300	9	28
2007	2	5	78	57	250	300	10	32
2008	2	7	65	60	300	300	12	44
2009	2	6	55	50	300	300	13	41
2010	2	8	45	48	300	300	14	56

Notes 1. ICP stands for Integrated Circuit Process
2. The Fab capacity index is computed by ranking IC process (largest to smallest) and wafer size (smallest to largest) , then summing these points over all fabs

Table 2: Evolution of Capacity Variables

2.4 Exclusive Restrictions

We examined case files from the Department of Justice and the European Commission that listed the types of exclusive restrictions Intel imposed on downstream PC firms. From these files we could categorize the type of restrictions imposed, which include a cap on amount sold of AMD or restrictions on sales in specific segments/product lines, restrictions on distribution channels used for AMD products, provision of rebates in exchange for selling certain amounts of Intel-based machines, limitations on the marketing PC firms could undertake for AMD-based products, guarantees of preferred supply of Intel CPUs, and restrictions imposed on bidding on contracts using AMD-based products. These documents also detail threats made

[13] The quarterly filings were accessed on September 18, 2014 from http://ir.amd.com/

by Intel to certain PC firms to remove funding or channel funding to rivals or other retaliation as a punishment for selling more than the specified amount of AMD chip.

Based on these restrictions we form two indices - one is the sum of the number of restrictions imposed, and the other one is the sum of the number of more extreme restrictions. The latter includes: excessive rebates, demands to exclude AMD from certain product lines completely, threats, or a promise to increase Intel market shares provided to the PC firm. Table 1 reveals that, on average across brand-segment-quarters, 1.03 restrictions were in place while the maximum was 6. Figure 4 shows the number of brand segments which were affected by the exclusionary restrictions index in each quarter. As can be seen, most of the restrictions took place before 2007. The variation reflected in this figure allows the identification of the coefficient of the index in our model.

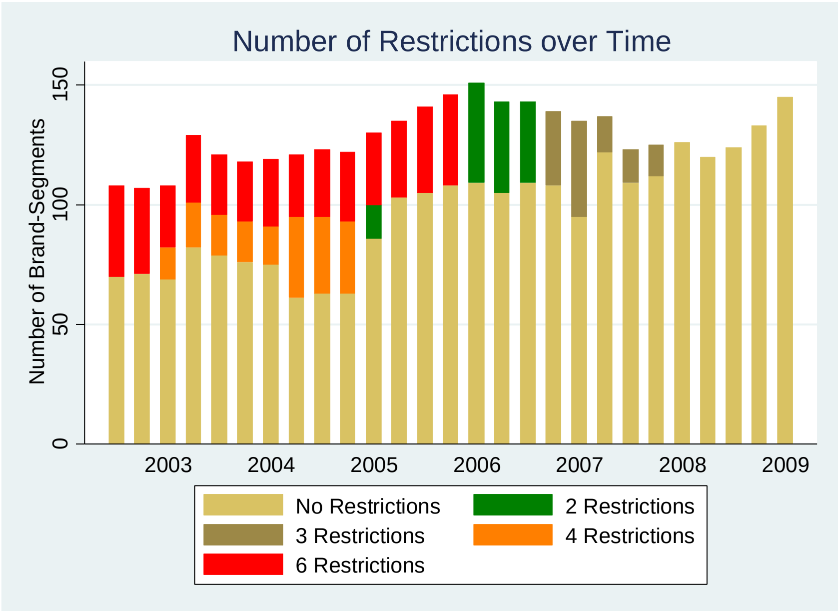

Figure 4: Evolution of Restrictions Imposed by Intel

We also observe rebates offered by Intel to PC firms via the Intel Inside program. In the case of Dell, the amounts of the exact payments are available from the court decision *SEC vs. Dell Inc. July 22 2010*, covering the years 2003 until 2007. After 2007 we refer to the official advertisement of the Intel Inside program on Intel's webpage. The program stated that 3% of the CPU costs of the PC firm would be offered by Intel to finance ads for PC models equipped with Intel CPUs.[14] Hence, for the period after 2007, the Intel Inside payments are computed as 3% of Dell's CPU costs (computed using Gartner sales data and the price dataset we described previously). An identical approach, using a 3% rebate, is used to compute the Intel Inside payments received by other PC firms. The variable is defined at the firm level and summed over all brands and segments.

Figure 5 proposes an overview of these Intel Inside payments. The payments are sorted into two groups: the payments to Dell on the left axis and the average payments to the other PC firms on the right axis. First, we note that the payments to Dell (over the 2003-2007 period) are close to 100 times the payments the company was supposed to receive based on the advertised 3% rebate. Examining payments to other PC firms (computed based on the 3% rebate), it appears that inclusion in the Intel Inside program conveyed non-negligible benefits: these payments averaged between \$2.3 and \$5.5 million per quarter per firm.

2.5 Legal Action

We compiled information on investigations or legal action taken against Intel relating to its practices against AMD. We construct two variables based on lawsuits filed by the Federal Trade Commission, European Commission, Korean Fair Trade Commission, Japanese Fair Trade Commission, State of New York, and found in the shareholder reports of both Intel and AMD. We include measures of the cumulative number of antitrust cases/investigations brought against Intel as of 2001 and the number of pending antitrust cases/investigations in process against Intel. These variables may capture the extent to which market participants revise their beliefs regarding the future viability of Intel's restraints. Table 1 shows that on average across all quarters there were 3.45 pending cases, and 4.19 cumulative cases.

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[14] For further details about the program, see for example Lee, Péchy and Sovinsky (2013).

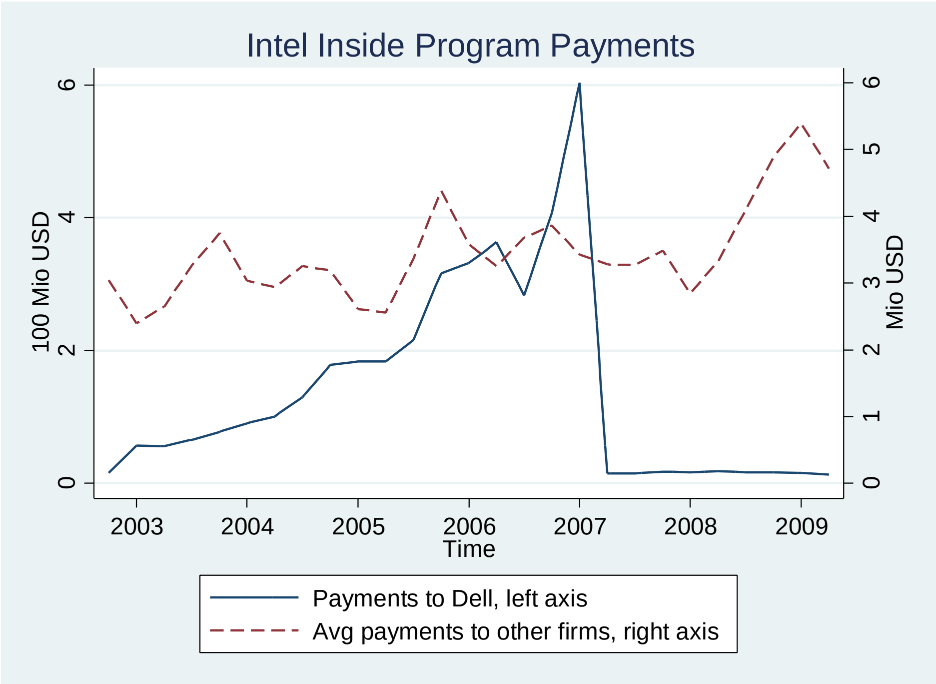

Figure 5: Evolution of Intel.s Payments to PC Firms

3 Econometric Model

3.1 Preliminaries

Our goal is to identify the effect of vertical restraints imposed by an upstream supplier (Intel) on downstream input adoption decisions. We, therefore, set up an econometric model that treats a PC brand-segment-quarter combination as the unit of observation, and defines the extent of the usage of AMD chips as the dependent variable. Specifically, we use the fraction of CPUs used in a PC brand-segment that are AMD-based. Defining the dependent variable in this way helps us link our analysis to the nature of Intel's vertical restraints, which often specified a cap on the extent of AMD chips used in each segment as a condition for eligibility to the Intel Inside program benefits. Intel's restrictions, for their part, are the key explanatory variable which effect we wish to capture.

Several econometric challenges arise in this analysis. A major challenge to overcome is the dynamic nature of PC makers' technology adoption decisions, which arise due to several reasons. First, beginning to use AMD chips (or expanding the extent of their adoption) requires a certain degree of investment by the PC maker. In particular, the PC maker must learn how to configure the hardware (e.g., the motherboard) to AMD's specifications, and set up (or expand) a production line that installs AMD chips. Since AMD and Intel chips are not "pin-compatible," one cannot simply plug one of them instead of the other, and certain adjustments need to be made. Such an investment in the learning and internal organization is not likely to be a static, period-by-period decision, but rather a cumulative process. Importantly, the infrastructure created in a given quarter (where by "infrastructure" we mean the accumulated know-how, experience and physical aspects of an AMD-based production line) is likely to be useful in future quarters as well, and to reduce the cost of employing the AMD technology in these future quarters. The adoption decisions are best viewed, then, as a dynamic process in which current investment decisions are taken given expectations regarding future market conditions, formed based on observing current values of key variables, some of which are endogenous. The state-dependent nature of these decisions manifests itself in several fashions. In particular, they imply that the endogenous adoption decisions at time $t-1$ affects the adoption decision at time t, and this dynamic link must be addressed via dynamic panel methods.

Another issue involves the nature of the expectations formed by the PC maker at time t regarding market conditions in future periods. This nature dictates the set of variables that we wish to include as explanatory variables for the current adoption decision. For a PC maker to be willing to place increased importance on AMD chips, it must believe that AMD would be able to meet the level of demand. PC makers' emphasis on keeping thin inventories implies that this issue is crucial for the creation of strategic dependence on AMD's chips.

Capacity constraints are, in general, an important aspect of the integrated circuit industry. During the sample period, AMD's market share hovered around 20%, and it strived to increase its production toward parity with Intel. Intel, however, enjoyed a substantial advantage in terms of production facilities (FABs). It is likely that AMD faced a "chicken-and-egg" dilemma: in order to increase its market share, it would have to expand its production capacity so as to convince downstream clients that they can rely on timely, large-scale shipments. Constructing chip production facilities, however, is extremely expensive, and with low sales, AMD may have lacked the financial capabilities to finance such investments. The market's expectations regarding AMD's ability to expand its capacity, therefore, may have played a crucial role in clients' adoption decisions. We address this issue by including measures of AMD's (Intel's) capacity as explanatory variables. This allows important events, such as the opening of a new AMD production facility, to affect current decisions by downstream clients' via its effect on their expectations regarding AMD's future growth potential.

Other key determinants of downstream adoption decisions is the performance of AMD and Intel chips. If AMD is able to introduce a new chip with superior capabilities, it affects not only the PC maker's current benefit from installing this new chip, but also its expectations regarding future benefits. Specifically, it increases the perceived probability that AMD would be able to increase its market share, allowing it to expand its investments in technology and capacity. On a similar vein, the price of the chips affect the current decision. A low AMD price may capture not only current downstream benefits (in the form of reduced PC marginal costs), but can also capture improved production processes: CPU innovation often leads to CPUs that are both faster and cheaper to produce (via the reduction of the die size). So, a lower AMD price may also indicate its ability to invest in new production technologies and improve its competitive standing, as well as its future survival and growth prospects. To capture both related effects, we include the sales weighted average of the benchmark per dollar for AMD and Intel as explanatory variables.

Finally, Intel's vertical restraints also play an important role on the right-hand-side of our econometric model. First, they may directly affect the extent of adoption of AMD chips, since they imply that using more than a certain amount of AMD chips may result in a loss of substantial monetary transfers via the Intel Inside program. Second, they also may affect expectations. If Intel aggressively increases payments via the program, it may signal to the market that it is determined to block AMD from expanding. If this signal is credible, it may discourage current adoption of AMD chips. We, therefore, include as explanatory variables not only the vertical restraints imposed on the PC firm in question, but also measures that capture the overall scope and magnitude of Intel's restraints and subsidies.

3.2 Formal econometric setup

Our unit of observation (i) is the PC brand-quarter-segment (e.g, Acer's Home Market Aspire), where the extent of usage of AMD chips at time t is the dependent variable, W_{it}.That is, we use the fraction of AMD-based CPUs used by each PC firm in each of their brands (by quarter-segment). Our model for the PC firm's choice is given by

$$W_{it} = \alpha W_{it-1} + \beta x_{it} + \lambda c_t + \eta m_{it} + \delta r_{it} + \gamma l_{it} + \mu_i + \varepsilon_{it.} \tag{1}$$

Following the above discussion, W_{it-1}, the lagged percentage of segment-brand i sold with an AMD processor, serves as an explanatory variable to help us capture the dynamic link between current and future decisions. The μ_i term represents brand fixed effects and ε_{it} is an idiosyncratic iid error term.

Time varying observed characteristics of PC brand i are captured by x_{it}.[15] These include the price of brand i, brand-level advertising, and firm-level advertising. Given that often more than one product is available within the brand, when the component of x_{it} varies across such products we compute the weighted average within the brand.

Variables relating to CPU manufacturing capacity constraints are included in c_t. To capture upstream production technology investments (along with their effect on expectations), we include a capacity index for AMD and for Intel, which is a function of the number of FABs, wafer size and IC process (as described in section 2), as well as the (lagged) amount of free cash available to AMD for investment. Our assumption, supported by institutional details, is that Intel was much less subject to cash constraints than AMD. Measures of capacity refer to worldwide capacity for production, while our variable of interest relates to sales in the US, which mitigates endogeneity concerns. Furthermore, several relevant strategies present themselves with respect to including lags and leads of these variables. One could argue that leads of capacity should be included, since the knowledge that AMD is about to expand its capacity may also affect decisions. On the other hand, one may argue that announcing that the new IC process would become "operational" on a given date, and announcing that it

[15] We do not include product characteristics that are not time varying within brands (such as the platform/form factor) because these are absorbed by the brand fixed effect term.

is operational on a given date, are very different pieces of information, which may justify using lagged values but not leads. For this reason, we estimate a variety of specifications with leads and lags of capacity variables.

CPU related variables are given in m_{it}. These include the extent of technological progress as measured by the benchmark per CPU dollar indices for Intel and AMD, respectively, the number of quarters the segment-brand-CPU family combination for those families sold by AMD has been available, and the number of quarters the segment-brand-CPU family combination for those families sold by Intel has been available.[16]

The vector r_{it} captures upstream restrictions and can be conceptually decomposed into two parts: the part related to exclusive restrictions on PC sales imposed by Intel and the part related to payments via the Intel Inside program. Identifying the impact of the upstream restrictions on product line choice is the goal of our analysis. Specifically, r_{it} contains total payments Intel made to the relevant PC maker, payments made to other downstream firms, indices that capture the intensity of exclusionary restrictions imposed by Intel (as discussed in section 2), and the number of such restrictions imposed on rival firms.

Finally, the vector l_{it} captures legal issues that may impact whether AMD is sold. These include the cumulative number of antitrust cases/investigations brought against Intel as of 2001 or the number of pending antitrust cases/investigations in process against Intel.

Identification. Our goal is to identify the causal effect of upstream vertical restraints on downstream product line choices (i.e., firm's input decisions). Our identification strategy takes advantage of the dynamic panel aspect of our data. This approach is valuable for a number of reasons. First, a dynamic panel can help us address unobserved firm heterogeneity in the decision to adopt AMD's chips. Unobserved heterogeneity may arise if some firms are fundamentally better-suited to gain from using AMD's chips. For example, this may stem from firms' natural positioning as "value PC" makers, which motivates them to offer PCs with cheaper CPUs installed (noting that AMDs prices are typically lower than those of Intel). In addition, some firms may have more flexible production processes than others (for instance, in the sense that they do not enjoy huge economies of scale from using only

[16] We do not have information prior to 2001 so the number of quarters available is counted starting from the first quarter in 2001.

one type of chip).

A challenge to the analysis is that the use of vertical restraints may be endogenous, and the panel data are crucial to our identification of the causality of vertical restraints on input decisions in this respect. In the absence of an instrument (that is correlated with the use of vertical restraints but not with quantity) cross-sectional data would only allow us to uncover correlations between vertical restraints and the dependent variable. The panel aspect of our data allows us to overcome the endogeneity issue by using a fixed-effect type of estimator. This removes time-invariant unobserved firm heterogeneity that is the cause of the endogeneity problem. Thus, the effect of the vertical restraint on the outcome variable, (as captured in δ) is causal and is identified by time-series variation. Note that we need time-series variation in the use of exclusive constraints, which we observe in the data.

We estimate specifications that address different aspects of the data and setup at hand. We begin by estimating the relationship in equation (1) using a linear approach followed by a non-linear approach (Tobit). The Tobit enables us to consider explicitly the issue of zero-adoption observations. Both approaches address endogeneity of the past-adoption decision W_{it-1} and of the exclusive deals (r_{it}). Furthermore, the approaches account for the issue that components of the x_{it} and f_{it} may also be endogenous as they relate to product line choices.

Linear specification. Our linear strategy treats μ_i as a fixed effect to be differenced out following Arellano and Bond (1991). Differencing out the fixed effects, we obtain a first-differences regression of the form:

$$\Delta W_{it} = \alpha_L \Delta W_{it-1} + \beta_L \Delta x_{it} + \delta_L \Delta r_{it} + \lambda_L \Delta c_t + \eta_L \Delta m_{it} + \Delta \varepsilon_{it}. \tag{2}$$

One could assume that the variables represented by $y_{it} \equiv \{x_{it}, r_{it}, c_t, m_{it}\}$ are strictly exogenous. That is, that ε_{is} is independent of y_{it} for any t, s conditional on μ_i. Strict exogeneity implies Δy_{it} is exogenous and hence Δy_{it} can be it's own instrument. However, Δy_{it} may be a weak instrument.[17] Another solution to potentially weak instruments is

[17] One can test the null hypothesis that the overidentifying restrictions hold using a Wald statistic which is valid under heteroskedasticity and clustering. The critical value is $\chi^2(l)$, where l is the degree of overidentification.

to assume that ε_{it} is independent over time, then the (two period) lag of the endogenous variable(s) is a valid instrument.[18]

However some of the regressors, even if independent of current disturbances, may be influenced by past ones. These regressors are then not strictly exogenous but rather exhibit sequential exogeneity where $E(\varepsilon_{it} \mid y_{is}, \mu_i) = 0$ for $s \leq t$. Relaxing the assumption of strict exogeneity implies Δy_{it} is endogenous. In this case one can use W_{it-2} and y_{it-1} as IV in the first-differenced equation.[19] We estimate specifications allowing for sequential exogeneity.

Note that estimators using too many lags of explanatory variables (relative to the number of observations) as instruments are known to have poor finite sample properties (Arellano and Bover (1995), and Blundell and Bond (1998)). In practice it is best not to use lags back to $t = 1$. We follow this approach and consider specifications using only lags of three periods.

Nonlinear specification. The linear specifications above allowed us to control for both state dependence, and for individual heterogeneity, in explaining the rate of adoption of AMD's chips. These specifications, however, did not address the "corner solution" issue: many product lines, at different times, chose not to use AMD chips at all.

To address this issue, we follow Wooldridge (2002) in specifying a dynamic nonlinear model that builds on Chamberlain (1984). This allows us to include random effects that capture time-constant heterogeneity, as well as a lagged dependent variable capturing state dependence. However, this framework does not allow us to relax a strict exogeneity assumption. In other words, both the linear and the nonlinear models have their specific strengths and weaknesses, and considering both approaches allow us to provide a more complete picture of the data patterns of interest.

This specification treats the dependent variable W_{it} similarly as in the linear specifications: it is a continuous measure with a mass point at zero given by

[18] In this case it is important to test the null hypothesis that ε_{it} is independent over time. We implement an autocovariance test of the null hypothesis of no autocorrelation in the idiosyncratic error term.

[19] We can test for weak instruments using the standard first stage regression results: if y_{it-1} are not weak instruments then they should affect W_{it-1} conditional on y_{it}. Again, we can test for serial correlation in the errors.

$$W_{it} = max\big(0, \alpha_{NL}W_{it-1} + \beta_{NL}x_{it} + \delta_{NL}r_{it} + \lambda_{NL}c_t + \eta_{NL}m_{it} + \mu_i + u_{it}\big) \tag{3}$$

$$u_{it}|(\overline{y}_i, W_{i,t-1}, ...W_{i0}, \mu_i) \sim N(0, \sigma_u^2), \tag{4}$$

where, as in the linear specification, we denote by y_{it} the collection of all the explanatory variables in all time periods. The mean (over time) of these variables is $\overline{y}_i$.

One issue concerns the initial value of W_{i0}. One possibility is to treat it as nonrandom, which would imply that μ_i and W_{i0} are independent. However, this may not necessarily be the case, so we specify the density of the fixed effect *conditional on the initial condition*. That is, we specify the fixed effects as

$$\mu_i = \psi + \xi_0 W_{i0} + \overline{y}_i\xi + a_i,\ \ a_i|\,(W_{i0}, \overline{y}_i) \sim N(0, \sigma_a^2). \tag{5}$$

As discussed in Wooldridge (2002), the fixed effects can then be integrated to yield the likelihood function of the random effects Tobit model with time-t, observation-i explanatory variables: $(y_{it}, W_{i,t-1}, W_{i0}, \overline{y}_i)$. That is, $\overline{y}_i$ and w_{i0} are controlled for in each time period. We will use this likelihood function to obtain estimates of the parameters $(\alpha_{NL}, \beta_{NL}, \delta_{NL}, \lambda_{NL}, \eta_{NL}, \psi, \xi_0, \xi, \sigma_a^2)$.

4 Results

Table 3 presents results from the linear specification. The estimates of α, the state-dependence factor, are on the order of 0.6-0.7 (noting that values between zero and one are considered valid). Considering the effect of PC characteristics, the PC price appears to have a weak (often insignificant) negative relationship with the intensity of AMD adoption. There is also a negative relationship of the AMD adoption with the intensity of brand and firm-level advertising. The effects of CPU characteristics are highly intuitive: AMD adoption increases (decreases) in the AMD (Intel) benchmark per dollar measure. Adoption of AMD is also more prevalent when the specific combination of the AMD CPU family and the PC brand-segment have been on the market longer, with the reverse pattern holding for the combination of the Intel CPU with the PC brand-segment. Examining capacity variables, we note that AMD's lagged free cash does not significantly affect AMD's adoption. On the other hand, and as expected, AMD's (Intel's) capacity index positively (negatively) affects the rate of AMD adoption.

Continuing to move down Table 3 we reach our main results, concerning the impact of Intel's vertical restraints. Both the restriction index and the extreme restriction index are found to have a negative and statistically significant effect on the rate of AMD's adoption. Simply put: restrictions placed by Intel on the intensity of AMD utilization of a given downstream client indeed bind, and reduce the fraction of AMD-based machines produced by the client. Payment to the client from the Intel Inside program also have a negative relationship with AMD adoption, which is not surprising given that these payments depend positively on the utilization of a substitute, the Intel technology.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Lagged Percentage AMD Sold	0.6956***	0.6905***	0.6598***	0.7143***	0.6728***	0.6714***	0.6814***	0.7039***	0.7047***	0.7201***	0.6597***	0.6604***
	(0.0727)	(0.0732)	(0.0770)	(0.0731)	(0.0793)	(0.0794)	(0.0804)	(0.0696)	(0.0703)	(0.0782)	(0.0754)	(0.0763)
PC Characteristics												
Price PC (100$)	-0.0043	-0.0048	-0.0073*	-0.0059	-0.0096**	-0.0067	-0.0073*	-0.0035	-0.0033	-0.0037	-0.0074*	-0.0071*
	(0.0036)	(0.0036)	(0.0042)	(0.0036)	(0.0044)	(0.0042)	(0.0041)	(0.0034)	(0.0035)	(0.0036)	(0.0042)	(0.0042)
Brand Advertising (10M$)	-0.0082**	-0.0086**	-0.0095**	-0.0058	-0.0084*	-0.0096**	-0.0090**	-0.0070**	-0.0071**	-0.0084**	-0.0095**	-0.0096**
	(0.0037)	(0.0038)	(0.0045)	(0.0038)	(0.0050)	(0.0043)	(0.0044)	(0.0036)	(0.0035)	(0.0037)	(0.0046)	(0.0045)
Firm Advertising (10M$)	-0.0017	-0.0029*	-0.0017	-0.0026*	-0.0021	-0.0018	-0.0012	-0.0021	-0.0021	-0.0026*	-0.0018	-0.0017
	(0.0013)	(0.0016)	(0.0015)	(0.0014)	(0.0015)	(0.0015)	(0.0014)	(0.0014)	(0.0014)	(0.0015)	(0.0015)	(0.0015)
CPU Characteristics												
AMD CPU benchmark/dollar (10,000$)	0.0041***	0.0041***	0.0043***	0.0036**	0.0037**	0.0041***	0.0039***	0.0042***	0.0042***	0.0038***	0.0043***	0.0043***
	(0.0014)	(0.0014)	(0.0015)	(0.0015)	(0.0016)	(0.0015)	(0.0015)	(0.0014)	(0.0014)	(0.0014)	(0.0015)	(0.0015)
Intel CPU benchmark/dollar (10,000$)	-0.0090***	-0.0092***	-0.0101***	-0.0095***	-0.0108***	-0.0099***	-0.0099***	-0.0087***	-0.0087***	-0.0086***	-0.0101***	-0.0101***
	(0.0022)	(0.0022)	(0.0024)	(0.0021)	(0.0023)	(0.0024)	(0.0024)	(0.0020)	(0.0021)	(0.0022)	(0.0022)	(0.0023)
Number Quarters Brand/AMD family available	0.0092***	0.0092***	0.0099***	0.0085***	0.0093***	0.0096***	0.0093***	0.0090***	0.0090***	0.0084***	0.0099***	0.0099***
	(0.0029)	(0.0029)	(0.0030)	(0.0029)	(0.0031)	(0.0031)	(0.0031)	(0.0028)	(0.0028)	(0.0030)	(0.0030)	(0.0030)
Number Quarters Brand/Intel family available	-0.0046***	-0.0048***	-0.0056***	-0.0044***	-0.0055***	-0.0053***	-0.0051***	-0.0044***	-0.0044***	-0.0041***	-0.0056***	-0.0056***
	(0.0014)	(0.0014)	(0.0016)	(0.0014)	(0.0016)	(0.0017)	(0.0017)	(0.0013)	(0.0013)	(0.0015)	(0.0015)	(0.0015)
Capacity Related Variables												
Lagged Free Cash (1000M$)	0.0141	0.0140	0.0128	0.0156	0.0148	0.0150	0.0151	0.0137	0.0135	0.0155	0.0129	0.0129
	(0.0106)	(0.0105)	(0.0103)	(0.0102)	(0.0100)	(0.0101)	(0.0103)	(0.0111)	(0.0116)	(0.0112)	(0.0109)	(0.0114)
AMD Capacity Index	0.0043***	0.0044***	0.0046***	0.0053***	0.0051***	0.0033**	0.0041***	0.0047***	0.0048***	0.0041***	0.0045***	0.0046***
	(0.0012)	(0.0012)	(0.0012)	(0.0011)	(0.0012)	(0.0015)	(0.0012)	(0.0012)	(0.0012)	(0.0012)	(0.0012)	(0.0012)
Intel Capacity Index	-0.0014**	-0.0014**	-0.0014**	-0.0017***	-0.0015**	-0.0013**	-0.0013**	-0.0015**	-0.0015**	-0.0013**	-0.0014**	-0.0014**
	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)
Exclusionary Restriction/Antitrust Related Variables												
Exclusionary Restriction Index	-0.0025**											
	(0.0010)											
Extreme Exclusionary Restrictions Index		-0.0064***								-0.0079***		
		(0.0024)								(0.0025)		
Intel Payments to PC Firms (M$)			-0.0015***		-0.0015***	-0.0017***	-0.0018***				-0.0015***	-0.0015***
			(0.0004)		(0.0005)	(0.0004)	(0.0004)				(0.0004)	(0.0004)
Intel Payments to Dell (100M$) (For Non-Dell Firms)				-0.0029*	-0.0027*							
				(0.0017)	(0.0016)							
Number Exclusionary Restrictions on Other Firms						-0.0013						
						(0.0010)						
Number Extreme Restrictions on Other Firms							-0.0047**			-0.0028		
							(0.0022)			(0.0024)		
Number Pending Antitrust Cases Against Intel								0.0004			0.0002	
								(0.0027)			(0.0027)	
Number of Antitrust Cases Against Intel									0.0001	0.0001		0.0001
									(0.0020)	(0.0019)		(0.0020)

Notes: Robust Clustered Standard Errors in Parentheses. Each regression contains a constant and a quarterly trend. *** denotes significance at the 1% level, ** at the 5% level; and * at the 10% level. Each regression contains 3236 observations.

Table 3: Arellano-Bond Regressions of Percentage of AMD Sold

Of particular interest is the finding that, conditional on own payments from Intel, Intel's payments to Dell have a negative (statistically significant at the 10% level) impact on the rate of AMD adoption by *other* downstream PC manufacturers (see specifications 4 and 5). Moreover, the number of restrictions imposed on *other* manufacturers also has a negative (albeit often insignificant) impact on the rate of AMD adoption by a given manufacturer (specification 7), again this result maintains after controlling for own Intel payments. These findings all point to the possible role of dynamics in the technology adoption process: from the point of view of a downstream client, knowing that Intel imposes strong restrictions on other clients' adoption of the AMD technology may signal that AMD could face difficulties in expanding its sales and financing future investments, therefore reducing the value of adopting the AMD technology today. Finally, the numbers of (pending and cumulative) litigation cases has the expected positive sign, although they are not statistically significant.

Table 4 reports results from the nonlinear (Tobit) specification. The coefficients capturing the effect of PC characteristics, CPU characteristics and capacity variables are qualitatively similar to those obtained from the linear specification. The results for the impact of the vertical restraints, however, carry some differences with respect to the linear specification results. First, the effect of Intel Inside payments remains negative and highly significant across specifications. Second, the effect of the restriction indices applying to the PC firm in question are once again negative, although insignificant. Restrictions imposed on other clients now have an insignificant effect, and the effect of payments to Dell on adoption decisions by other firms has the "wrong" sign. On the other hand, the litigation variables all have the expected positive and significant effect on AMD's adoption even conditional on own payment from Intel. In this sense, similarly to the linear specification, the nonlinear specification also carries the flavor of the importance of dynamics and client expectations, though it highlights different aspects of this issue (i.e., while it fails to capture the effect of restrictions on other clients in a significant fashion, it does capture the significant effect of antitrust litigation).

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Lagged Percentage AMD Sold	0.660***	0.622***	0.620***	0.619***	0.623***	0.622***	0.626***	0.627***	0.620***	0.619***
	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)
PC Characteristics										
Price PC (100$)	-0.042***	-0.043***	-0.041***	-0.042***	-0.041***	-0.041***	-0.042***	-0.042***	-0.042***	-0.041***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Brand Advertising (10M$)	-0.031	-0.041	-0.042	-0.041	-0.038	-0.041	-0.036	-0.038	-0.038	-0.040
	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)	(0.028)
Firm Advertising (10M$)	0.007	-0.000	-0.001	-0.001	0.001	-0.001	0.002	-0.000	0.000	-0.001
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.004)	(0.005)	(0.004)	(0.004)	(0.004)
CPU Characteristics										
AMD CPU benchmark/dollar (10,000$)	0.023***	0.023***	0.023***	0.023***	0.023***	0.023***	0.023***	0.023***	0.024***	0.024***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Intel CPU benchmark/dollar (10,000$)	-0.017***	-0.019***	-0.018***	-0.018***	-0.018***	-0.018***	-0.019***	-0.019***	-0.018***	-0.018***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number Quarters Brand/AMD family available	0.009***	0.009***	0.009***	0.009***	0.010***	0.009***	0.009***	0.009***	0.009***	0.009***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number Quarters Brand/Intel family available	-0.012***	-0.012***	-0.012***	-0.012***	-0.012***	-0.012***	-0.012***	-0.012***	-0.012***	-0.012***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Capacity Related Variables										
Lagged Free Cash (1000M$)	0.021	-0.011	0.006	0.005	0.009	0.005	-0.010	-0.018	-0.015	0.001
	(0.024)	(0.024)	(0.025)	(0.026)	(0.025)	(0.025)	(0.026)	(0.025)	(0.024)	(0.025)
AMD Capacity Index	0.024***	0.021***	0.019***	0.019***	0.018***	0.019***	0.020***	0.021***	0.018***	0.017***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.004)	(0.004)	(0.005)
Intel Capacity Index	-0.008***	-0.007***	-0.007***	-0.007***	-0.007***	-0.007***	-0.007***	-0.007***	-0.006***	-0.007***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Exclusionary Restriction/Antitrust Related Variables										
Intel Payments to PC Firms (M$)		-0.018***	-0.020***	-0.019***	-0.020***	-0.020***	-0.018***	-0.018***	-0.018***	-0.019***
		(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Exclusionary Restriction Index					-0.006		-0.005			
					(0.005)		(0.006)			
Extreme Exclusionary Restrictions Index						-0.002		0.001		
						(0.014)		(0.014)		
Intel Payments to Dell (100M$) (For Non-Dell Firm									0.007**	0.004
									(0.003)	(0.003)
Number Exclusionary Restrictions on Other Firms							0.000			
							(0.003)			
Number Extreme Restrictions on Other Firms								0.005		
								(0.006)		
Number Pending Antitrust Cases Against Intel			0.025***		0.025***	0.025***				0.021**
			(0.008)		(0.008)	(0.008)				(0.009)
Number of Antitrust Cases Against Intel				0.014**						
				(0.007)						

Notes: Robust Clustered Standard Errors in Parentheses. Regressions include quarterly trends, a constant, and mean regressors over time. *** denotes significance at the 1% level, ** at the 5% level; and * at the 10% level. Each regression contains 3236 observations.

Table 4: Tobit Estimates of Percent of AMD sold

As discussed in the Introduction, to the extent that Intel's restrictions impact AMD's production capacity (say, by signaling to the market that AMD may not be able to expand, limiting its access to credit), our inclusion of the capacity variables may lead to an underestimation of the effect of the restraints. In Table 5 we report Tobit estimates where we remove the capacity variables. The results provide strong support for our intuition. For example, specification (12) shows the following: the number of restrictions imposed on the downstream client itself, the amount of Intel Inside payments to this client, and the restrictions imposed on *other clients,* all have a negative, statistically significant effect on the extent of AMD adoption. This specification also re-validates the positive and significant effect of antitrust litigation against Intel on the extent of AMD's adoption. These results are robust across specifications.

As discussed extensively in the introduction and above in this section, the latter two effects (restrictions on other clients and litigation) have a clear dynamic flavor. A downstream client revises its expectations regarding AMD's future success upwards in response to increased antitrust litigation against Intel, since the latter implies that the restraints placed by Intel may be removed (which, indeed, happened to a large extent during our sample period, recalling section 2). This may cause the client to adopt the AMD technology more intensely today. Observing that Intel imposes more restrictions on other clients' usage of AMD chips operates in the opposite direction: it causes the client to revise downward its expectations regarding AMD's future standing in the market, leading to lower adoption of its technology today.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Lagged Percentage AMD Sold	0.678***	0.677***	0.681***	0.681***	0.680***	0.631***	0.629***	0.676***	0.634***	0.625***	0.632***	0.632***
	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)	(0.033)
PC Characteristics												
Price PC (100$)	-0.041***	-0.042***	-0.040***	-0.041***	-0.041***	-0.041***	-0.042***	-0.039***	-0.040***	-0.042***	-0.040***	-0.041***
	(0.005)	(0.005)	(0.004)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.005)	(0.005)
Brand Advertising (10M$)	-0.019	-0.020	-0.013	-0.012	-0.012	-0.032	-0.033	-0.017	-0.030	-0.029	-0.030	-0.029
	(0.028)	(0.028)	(0.029)	(0.029)	(0.029)	(0.028)	(0.028)	(0.029)	(0.028)	(0.028)	(0.028)	(0.028)
Firm Advertising (10M$)	0.002	0.002	0.006	0.006	0.006	-0.006	-0.005	0.006	-0.001	-0.002	-0.002	-0.002
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.004)	(0.005)	(0.005)
CPU Characteristics												
AMD CPU benchmark/dollar (10,000$)	0.020***	0.020***	0.019***	0.019***	0.020***	0.021***	0.021***	0.019***	0.020***	0.022***	0.020***	0.021***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Intel CPU benchmark/dollar (10,000$)	-0.019***	-0.019***	-0.020***	-0.019***	-0.019***	-0.020***	-0.020***	-0.019***	-0.021***	-0.019***	-0.020***	-0.020***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number Quarters Brand/AMD family available	0.009***	0.009***	0.009***	0.010***	0.010***	0.009***	0.009***	0.010***	0.009***	0.009***	0.010***	0.010***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number Quarters Brand/Intel family available	-0.011***	-0.011***	-0.011***	-0.011***	-0.011***	-0.011***	-0.011***	-0.011***	-0.011***	-0.012***	-0.011***	-0.011***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Exclusionary Restriction/Antitrust Related Variables												
Exclusionary Restriction Index			-0.010**	-0.010*	-0.009*			-0.013**	-0.013**		-0.011**	-0.011**
			(0.005)	(0.005)	(0.005)			(0.005)	(0.005)		(0.005)	(0.005)
Intel Payments to PC Firms (M$)						-0.022***	-0.021***		-0.020***	-0.018***	-0.021***	-0.021***
						(0.003)	(0.003)		(0.003)	(0.003)	(0.003)	(0.003)
Number Exclusionary Restrictions on Other Firms								-0.006***	-0.006***		-0.005**	-0.004**
								(0.002)	(0.002)		(0.002)	(0.002)
Intel Payments to Dell (100M$) (For Non-Dell Firms)										0.014***		
										(0.003)		
Number Pending Antitrust Cases Against Intel	0.015**			0.014*		0.028***					0.021***	
	(0.008)			(0.008)		(0.008)					(0.008)	
Number of Antitrust Cases Against Intel		0.014**			0.013**		0.024***					0.018***
		(0.006)			(0.006)		(0.006)					(0.007)

Notes: Robust Clustered Standard Errors in Parentheses. Estimates of cut-off point and quarterly trend are not reported. *** denotes significance at the 1% level, ** at the 5% level; and * at the 10% level. Each regression contains 3236 observations.

Table 5: Tobit Estimates of Percent of AMD sold Revisited

5 Conclusions

In this paper, we examine the impact of exclusionary restrictions put in place by Intel on PC firms in the semiconductor industry. We investigate the manner by which such restraints interact with the dynamic process of downstream technology adoption. To do so we use rich data on PC and CPU sales to estimate dynamic panel models that document such patterns in the semiconductor industry. Our analysis covers the years 2002-2009 and focuses on the role played by the "Intel Inside" program.

We find that the exclusionary restrictions used by Intel were binding in that they reduced the rate of AMD adoption. Our results also suggest that the vertical restraints had a dynamic impact in that they influenced downstream clients' expectations about the viability of AMD. Specifically, we find that (i) the adoption of the AMD technology by a given downstream firm was negatively affected by restrictions imposed on other downstream firms, and that (ii) the adoption was an increasing function of the intensity of antitrust litigation against Intel. We interpret these preliminary findings as reflecting the importance of dynamics in the technology adoption process and the importance of vertical restraints in influencing the nature of competition in an industry.

6 Appendix: Data Details

Advertisement Variables. We describe the creation of the advertisement variables based on a dataset from the Kantar Media Group. We identify three types of ad expenditures in the Kantar data: PC brand level advertising (Ad1), PC advertising categorized as business-to-business (Ad2) and PC firm level promotions (Ad3). We define two advertisement variables: brand specific advertising and firm level advertising. For brand specific advertising, we create the variable differently depending on whether the observation is in the home or non-home segment. Indeed, while Ad1 expenditures are likely to influence choices on both segments (households or firms), the Ad2 expenditures should only affect the non-home segment.

The firm level advertising are identically defined on both segments and consist of Ad3. The definitions of the two variables are summarized in Table A1. For those observations of the advertisement data whose brand could not be matched with the Gartner data, the expenditures were accounted for as firm level expenditures. Finally, the above described ad variables were matched to the Gartner data at the brand level. As the Kantar data contains less details about PC brands than the Gartner dataset, the match occurred based on the Kantar brands.

Variable / Segment	Home Segment	Non-home segment
Brand Advertising	Ad1	Ad1+Ad2
Firm Advertising	Ad3	Ad3

Table A1: Segment-specific Definition of Advertisment Variables

CPU Quality. We measure CPU quality in terms of CPU benchmark per dollar. In what follows we describe first the creation of the CPU family level price measures, and then the CPU family level benchmark measures.

To our knowledge, a comprehensive CPU price database for the US in the time period of interest is not available. We thus create our own CPU price dataset. We use four different sources: Instat estimated Intel CPU core prices (D1), Instat forecasted Intel CPU core prices (D2), Intel list prices (D3) and AMD list prices (D4). Table A2 offers an overview of their respective coverage. The level of aggregation of these datasets differs from one to the other and from that of the Gartner data. In what follows, we describe how each of these datasets was merged to the Gartner data to obtain a consistent dataset at the CPU family-quarter level. In the case of Intel, we also discuss how the different sources (Instat and List prices) are merged to generate a unified dataset.[20]

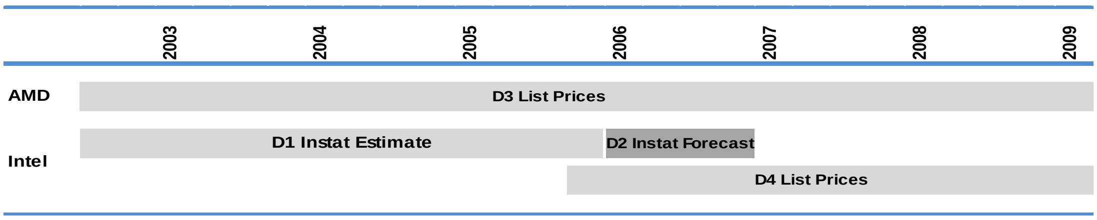

Table A2: Time Coverage of the Price Data Sources

We first describe the treatment of the Intel prices for 2002Q3-2005Q4 (D1). These are computed based on information from Instat's "Rosetta Stone" report on CPU core prices. We follow the methodology described in Lee, Pechy and Sovinsky (2013). A given CPU core is often marketed under different family names depending on which features are available. For example, the CPU core "Northwood"is used in both "Pentium 4"and "Mobile Celeron" CPU families. Moreover, the CPU core used in a CPU family can change over time. Taking these into consideration, the CPU cores are matched to the CPU families of the PC data at the platform group (whether deskptop or mobile)/type (mainstream/value/ultraportable)/ family/speed/quarter level.[21]

Table A3 provides the product cross-referencing. Table A4 provides an overview of the variation of the prices of these CPU model price estimates at the family level. The most famous Intel families, Celeron and Pentium 4, have more than a hundred price observations. Prices vary significantly within a family. The Pentium D model has only two observations

[20] The Gartner sales data also records a few CPU families which are neither Intel nor AMD produced (Cru, Eff, ViaC7). These observations are dropped due to lack of price information.

[21] For the CPUs not matched at first attempt, the type is dropped. When unmatched, the data are matched based on family/marketing name of a CPU, CPU speed, year, and quarter, ignoring platform group. When the data are not matched, we try matching based on platform group, family/marketing name of a CPU, CPU speed, ignoring time. For observations still not matched, we take the averages of prices estimates of CPUs of the same marketing name, year and quarter.

as it is introduced at the end of the sample.

Platform		CPU Core	Family Name	Speed (Frequency: MHz)
Desktop	Mainstream	Willamette		1300 - 2000
		Northwood	Pentium 4	1600 - 3400
		Prescott		2260 - 3800
		Smithfield*	Pentium D	2667 - 3200
	Value	Tualatin	Pentium III	1000 - 1400
			Celeron	900 - 1400
		Willamette	Celeron	1500 - 2000
		Northwood		1600 - 2800
		Prescott	Celeron D	2133 - 3460
Mobile	Mainstream	Northwood	Mobile Pentium 4-M	1200 - 2600
		Prescott	Mobile Pentium 4	2300 - 3460
		Banias	Pentium M	1200 - 1800
		Dothan		1300 - 2267
	Value	Tualatin	Mobile Celeron	1000 - 1330
			Mobile Pentium III-M	866 - 1333
		Northwood	Mobile Celeron	1400 - 2500
		Banias	Celeron M	1200 - 1500
		Dothan		1200 - 1700
	Low-Power	Tualatin LV	Mobile Pentium III-M	733 - 1000
		Tualatin ULV		700 - 933
		Tualatin LV	Mobile Celeron	650 - 1000
		Tualatin ULV		650 - 800
		Banias LV	Pentium M	1100 - 1300
		Banias ULV		900 - 1100
		Dothan LV		1400 - 1600
		Dothan ULV		1000 - 1300
		Banias ULV	Celeron M	600 - 900
		Dothan ULV		900 - 1000

Notes: * Dual-core processor
Low-power mobile PCs are mini-notebook, tablet, and ultraportables.
(LV: low-voltage; ULV: ultra-low-voltage)

Table A3. Cross-Reference from CPU Core to Family Name in 2002Q3-2005Q4

The price datasets from list prices of Intel and AMD (D3 and D4) were created as follows. Intel prices were collected in the form of Intel's price catalogues (unit price in case of 1000

CPU Firm	CPU Family	Median	Std Dev	Min	Max	Obs
Intel	Cel	66	7	49	77	140
	Cel M	94	32	87	203	12
	P3	128	46	49	170	36
	P4	176	17	130	202	171
	PD	245	4	242	247	2
	PM	219	29	190	317	51

Table A4: Descriptive Statistics of CPU Instat Estimated Prices by CPU Family in $

units) from a large variety of websites.[22] AMD prices (unit price in case of 1000 units) were collected from the corporate website list price publications using waybackmachine.com, a website storing (many) historical saves of given webpages. These list prices are published and observed at the CPU model level (e.g. AMD Athlon 64 2800+) with variable frequency and must be merged to the Gartner market share dataset at the CPU family level (e.g. AMD Athlon 64) observed quarterly.

Figure A1 provides an overview of the availability of list prices resulting from our data sources. The left panel depicts the number of publications observed in a quarter.[23] It reveals that for the majority of quarters, more than one price publication is observed. For both AMD and Intel, there is one period where no publication could be collected: 2008Q3 and 2007Q1 respectively. The treatment of these two periods is discussed below. In 2008Q3, nine price publications are observed for Intel. The right panel shows the quarterly average number of CPU models per publication per quarter: the price of a family is based on average on more than ten CPU models. For AMD in particular, this number declines over time. This is explained by changes in the product portfolio. Before 2003Q4 only one or two families were marketed, but these proposed many different models. Afterwards, more families were gradually introduced (seven families observed in 2008Q2) with lower number of models per family.

We propose an overview of the differences across families in these model-quarter level

[22] Complete list available from the authors upon request.

[23] We note that Intel list prices could not be collected prior to 2005Q4. Most likely, the company was not publishing list prices in PDF format on the web prior to this quarter.

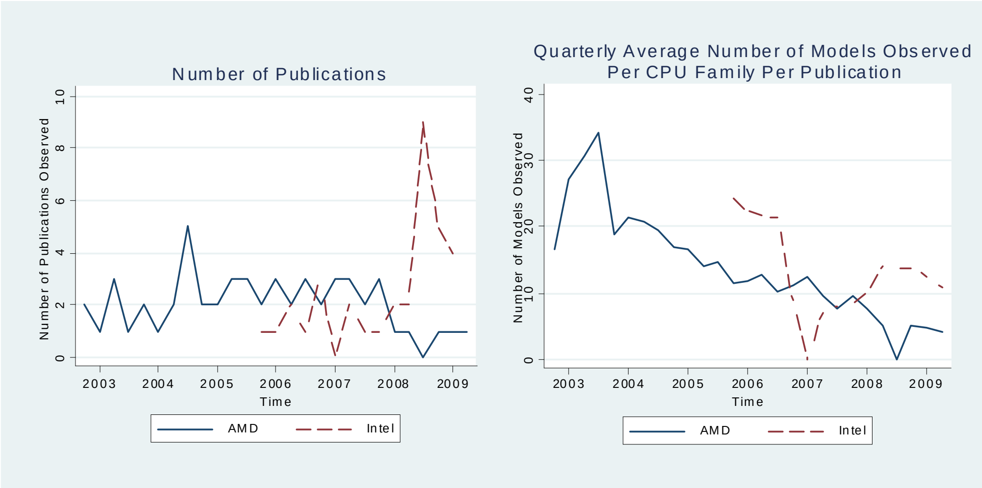

Figure A1: Availablity of List Price Data

prices in Table A5. Most families have at least 50 observations and some of them more than 500. Model prices are widely spread, which is explained by high prices at the introduction and a strong decline over time.

We now describe the aggregation of the list prices. The procedure is identical for AMD and Intel CPUs. The CPU prices at the publication date-model level are aggregated to the quarter-family level by taking the median over models. Second, the obtained price dataset is merged with the Gartner market share data at the family quarter level to verify price data availability for each quarter of a family's market share sequence. Out of 164 Intel CPU family-quarter observed in the Gartner data, 124 have a match in our Intel list price dataset. These numbers are respectively 164 and 148 for AMD CPU family-quarters.

For the periods of a sequence where price data is not available, we proceed as follows. When the price is missing in the middle of the sequence, it is approximated with kernel density interpolation at the family level. For prices missing in the first quarters of the sequence, the first observed price is used. These new introductions have usually very small market shares and high prices, which are preserved by this approximation. For prices missing in the last periods of the sequence, the last observed price is used. In a few cases where for a CPU family no price at all is observed the observations are dropped from the dataset (the related market shares are negligible, as these mostly concern server CPUs). These necessary

CPU Firm	CPU Family	Median	Std Dev	Min	Max	Obs
AMD	Ath	97	66	51	588	583
	Ath 64	223	210	36	1'031	579
	Ath 64 X2	178	193	62	1'001	269
	Dur	62	14	42	89	12
	Phe II X4	195	28	175	245	5
	Phe X3	122	23	101	195	24
	Phe X4	173	29	142	251	38
	Sem	86	26	30	145	617
	Tur 64	184	63	145	525	239
	Tur 64 X2	220	60	154	354	93
Intel	Atom	40	37	20	135	179
	Cel	65	26	30	134	479
	Cel M	107	34	45	161	178
	Cel X2	83	3	80	86	4
	Core 2 Duo	262	196	113	999	1'226
	Core 2 Quad	316	434	163	1'499	336
	Core 2 Solo	262	9	241	262	16
	Core Duo	294	129	209	706	184
	Core Solo	241	25	209	278	51
	Core i7	562	298	284	999	26
	P4	218	186	55	999	179
	PD	178	176	74	999	80
	PDC	64	9	64	86	137
	PM	304	114	130	702	409

Table A5: Descriptive Statistics of CPU Model List Prices by CPU Family in $

inter/extrapolations are listed in Table A6 for AMD and Table A7 for Intel. In the end, we obtain from the list prices, a dataset at the family quarter level with the following coverage: 2005Q4 until 2009Q1 for Intel, and 2002Q3 until 2009Q1 for AMD.

At this point, the Intel price data stem from two different sources: Instat for 2002Q3-2005Q4 (D1) and list prices for 2005Q4-2009Q1 (D3). To obtain a consistent measure of CPU prices, we define a correction coefficient. We take the mean of the "Instat price / list price" ratios at the CPU family level for periods where both types of prices are available. As this is only fulfilled in period 2005Q4, we propose a second correction coefficient on periods 2005Q4-2006Q4 using the Instat CPU core price predictions for year 2006 (D2). To obtain prices at the CPU family level, a cross-referencing between Gartner and Instat is executed as previously described except for speed information, which is not available in the Gartner data for 2006.

As for some CPU families more than one core is matched, the mean price over cores is retained. The cross-referencing is provided in Table A8. Using these prices, the second correction coefficient can be computed. The two price correction coefficients are summarized in Table A9. The Instat prices are on average 22% below the value of the list prices (14% when the Instat predicted prices (D2) are also included). As expected, the standard deviation of the coefficient which is computed over both estimated and predicted Instat prices is larger. The observed Min and Max values are to our understanding due to CPU model introductions being predicted too early/late, thus leading to a large value of the price difference for this CPU family. Based on these two price correction coefficients two different variables for Intel CPU family prices are defined. For robustness, we run our regressions using each variable.

	CPU Family Name	Quarter
First Value		
	Ath 64 X2	2005Q1
Interpolation		
	Ath 64, Ath 64 X2, Phe X3	2008Q3
	Phe X4, Sem	2008Q3
Last Value		
	Ath	2005Q3-2006Q1
	Tur 64	2007Q3-2008Q2
	Tur 64 X2	2008Q3-2009Q1
Dropped Obs		
	-	-

Table A6: AMD List Price Corrections

Benchmark. CPU benchmark information is gathered from Passmark publications.[24] This company collects measurements on CPU tests from users around the world, and creates a database of CPU performance at the CPU model level. We now discuss the treatment of the CPU benchmark information. The benchmark level of a given CPU family in a given period is built with two different approaches, exploiting the best information available in each quarter.

[24] Source: https://www.cpubenchmark.net/

	CPU Family Name	Quarter
First Value		
	Cel X2	2008Q2-2008Q4
	Core 2 Quad	2007Q1
	PDC	2007Q1-2007Q2
Interpolation		
	Cel, Cel M, Core 2 Duo	2007Q1
	Core Duo, Core Solo, P4, PD	2007Q1
Last Value		
	Core Duo	2008Q3-2009Q1
	Core Solo	2008Q3-2009Q1
	P4	2008Q3-2008Q4
	PD	2007Q3-2008Q1, 2008Q3-2009Q1
	PM	2006Q4-2008Q1, 2008Q3-2009Q1
Dropped Obs		
	A110	2007Q3-2008Q2

Table A7: Intel List Price Corrections

Platform		CPU Core	Family Name
Desktop	Mainstream	Conroe*	Celeron
		Conroe*	Core 2 Duo
		Prescott	Pentium 4
		Presler*	Pentium D
		Gallatin	Xeon
	Value	Cedar Mill	Celeron D
		Cedar Mill	Pentium 4
		Prescott	Celeron D
Mobile	Mainstream	Yonah*	Core Duo
		Dothan	Pentium M
	Value	Dothan	Celeron M
		Yonah	Celeron M
		Yonah	Core Solo
	Low-Power	Dothan LV	Pentium M
		Dothan ULV	Celeron M
		Dothan ULV	Pentium M
		Yonah LV	Xeon
		Yonah ULV	Celeron M
		Yonah ULV	Core Solo

Notes: * Dual-core processor
Low-power mobile PCs are mini-notebook, tablet, and ultraportables.
(LV: low-voltage; ULV: ultra-low-voltage)

Table A8: Cross-Reference from CPU Core to Family Name in 2006Q1-Q4

Used Instat Prices	Instat Price/List Price Ratio Overlapping Quarters	Mean	Std. Dev.	Min	Max	Obs
Estimated Instat Prices	2005Q4	0.78	0.24	0.58	1.15	5
Estimated and Predicted Instat Prices	2005Q4-2006Q4	0.86	0.45	0.40	2.30	33

Table A9: CPU Price Correction Coefficients

In the first approach, we rely on Gartner data information and match CPU benchmark to the Gartner data at the CPU family-CPU speed-platformgroup level (let us call this approach Gartner based) following Lee, Pechy and Sovinsky (2013). In the second approach, the availability of CPU models over time is inferred from our list price dataset described above (let us call this approach List Price based): those CPU models which are available in the period according to the list price information are those which define the value of the benchmark of that family in that period. The matches between the CPUs of the benchmark and the list price data are achieved by taking the best of 3 different matching criteria (in order of preference): family/model code/speed, family/model code, family/speed.[25] Then, to obtain the level of observation of the Gartner dataset after 2005 (without speed information), a CPU family quarter, we take the median of the benchmark level over CPU models in each quarter.[26]

Table A10 offers an overview of the approach used in each time period for each CPU firm. For AMD, the Gartner based approach is used from the beginning of the sample until 2005Q1, as in this quarter, speed information is not available anymore and thus the List Price based approach is preferred. For Intel, the Gartner based approach is used until 2005Q4, as this is the first period where Intel list prices are observed and thus the List Price

[25] Note that this last criteria is required in a minority of cases only. It can potentially aggregate very different benchmark levels (aggregating benchmarks of CPUs available in 2005 with some of 2008). To exclude these cases, we only use observations where the min and the max benchmarks are distant by less than 10%.

[26] For observations where benchmark information is missing, we use the same procedure as described above for prices (interpolation, first observed benchmark, last observed benchmark) since the benchmark data availability is corresponding to price data availability.

based approach is applied that period onwards.

	2003	2004	2005	2006	2007	2008	2009
AMD	*Gartner based*		*List Price based*				
Intel	*Gartner based*			*List Price based*			

Table A10: Methodologies used To Proxy Benchmark Level

Table A11 offers a summary of the benchmark scores of each family in the Gartner based approach . Table A12 offers a summary of the benchmark scores in the List Price based approach. There are clear differences across families. For example, Athlon models have low scores, while Phenom models are top performers. Differences within a family are less large but show that, as expected, various benchmark levels are proposed within a family.

CPU Firm	CPU Family	Median	Std Dev	Min	Max	Obs
AMD	Ath	410	119	200	610	14
	Ath 64	527	100	418	764	10
	Dur	272	17	243	272	3
	Sem	426	11	412	434	4
Intel	Cel	258	54	186	409	27
	Cel M	342	86	231	437	4
	P3	243	42	162	296	12
	P4	311	149	133	641	26
	PD	905	-	905	905	1
	PM	356	130	226	596	9

Table A11: Descriptive Statistics of CPU Benchmark Scores by CPU Family in the *Gartner based* Approach

Benchmark per Dollar Measure. Before getting to the merger of the price and the benchmark information, we provide a summary of the CPU landscape in Figure A2. The median price and the median benchmark (horinzontal and vertical axis respectively) are shown for the CPU families of both Intel and AMD for two periods 2004Q1 and 2008Q2 (left and right panel respectively). As can be seen, the number of families on the market

CPU Firm	CPU Family	Median	Std Dev	Min	Max	Obs
AMD	Ath	428	35	341	454	45
	Ath 64	559	249	445	1'597	388
	Ath 64 X2	1'264	197	805	1'781	266
	Phe II X4	3'602	329	3'100	3'941	5
	Phe X3	1'938	135	1'655	2'095	24
	Phe X4	2'585	259	2'168	3'047	38
	Sem	441	38	362	604	541
	Tur 64	467	64	387	616	239
	Tur 64 X2	894	138	768	1'273	93
Intel	Atom	304	120	163	634	155
	Cel	556	227	321	1'227	460
	Cel M	425	69	221	482	135
	Cel X2	1'220	54	1'173	1'267	4
	Core 2 Duo	1'547	488	587	2'652	1'049
	Core 2 Quad	3'575	478	2'976	4'606	253
	Core 2 Solo	316	84	311	502	16
	Core Duo	843	159	544	1'144	170
	Core Solo	402	86	280	514	46
	Core i7	6'123	547	5'555	7'022	26
	P4	548	86	180	688	134
	PD	809	83	672	1'000	80
	PDC	1'249	289	907	1'944	137
	PM	448	90	248	596	409

Table A12: Descriptive Statistics of CPU Benchmark Scores by CPU Family in the *List Price based* Approach

is much larger in 2008Q2. There is significant variation across families as some are low-end (low price and low benchmark level) while others are high-end (ex: Phe X4, Core 2 Duo).[27]

To account for this information in our model, we define a benchmark per dollar variable. For each CPU family quarter, the ratio of benchmark per price is computed. Then the data is merged with the Gartner sales data, and we compute the average of this ratio weighted by market share of all PC models in a PC brand-segment. We obtain the variables of interest, the benchmark per dollar for AMD (resp. Intel) at the PC brand-segment level. For a PC brand segment quarter where no AMD equipped PCs (resp. Intel) are offered, the benchmark

[27] We note that on a given benchmark level, a given CPU manufacturer provides various families at different price levels. The existence of the more expensive families is explained by the fact that beside the benchmark, other CPU characteristics influence the price (ex: power consumption). These could not be accounted for here due to lack of data.

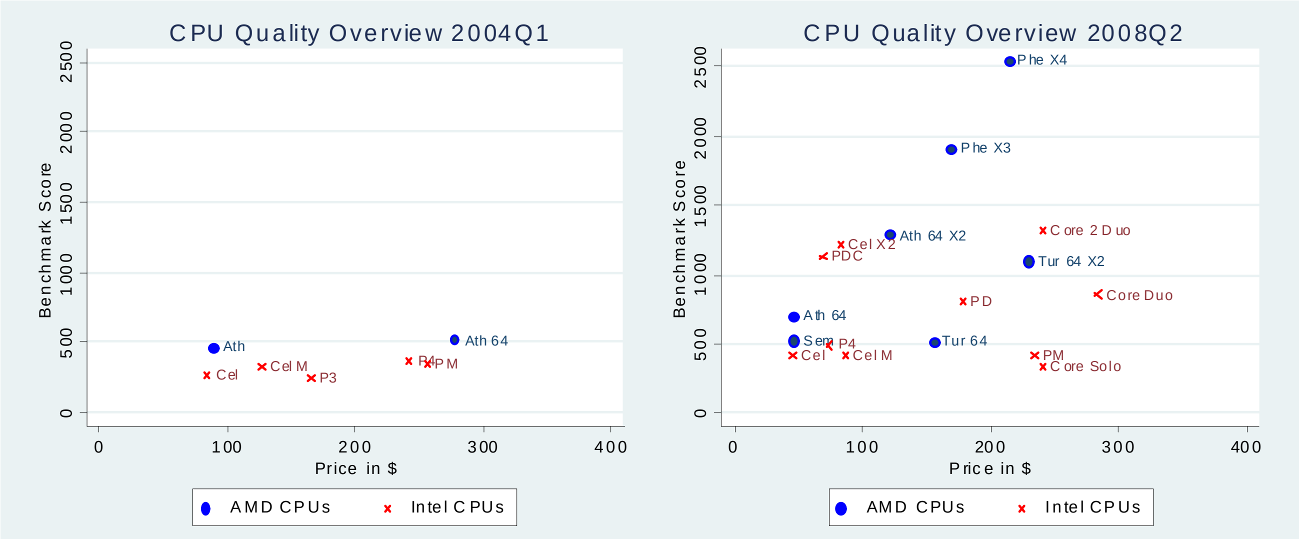

Figure A2: CPU Quality At The Family Level

per dollar variable is set to zero.

References

Arellano, M., and O. Bover (1995) "Another look at the Instrumental Variables Estimation of Error Components Models," *Journal of Econometrics* 68: 29-51.

Asker, J. (forthcoming) "Diagnosing Foreclosure due to Exclusive Dealing," *Journal of Industrial Economics.*

Ater, I. (2015) "Vertical Foreclosure in Shopping Malls: Evidence from Shopping Malls," *Journal of Economics and Management Strategy*, 24: 620 - 642.

Arellano, M. and S. Bond (1991) "Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations," *Review of Economic Studies* 58: 277-97.

Blundell, R. and S. Bond (1998) "Initial Conditions and Moment Restrictions in Dynamic Panel Data Models," *Journal of Econometrics* 87: 11-143.

Chamberlain, G. (1984) "Panel Data," in Z. Griliches and M.D. Intriligator (eds.), Handbook of Econometrics, Volume 2. Amsterdam: North Holland, 1247-1318.

Eizenberg A. (2014) "Upstream Innovation and Product Variety in the United States Home PC Market," *The Review of Economic Studies*, 81(3): 1003-1045

Lafontaine, F. and M. Slade (2008) "Exclusive Contracts and Vertical Restraints: Empirical Evidence and Public Policy," in Paolo Buccirossi, ed., Handbook of Antitrust Economics, Cambridge: MIT Press.

Lee, H., Pechy, A., and M. Sovinsky (2013) "Is Intel's Marketing Campaign Predatory?" Working Paper, University of Zurich.

Goettler, R. and B. R. Gordon (2011) "Competition and innovation in the microprocessor industry: Does AMD spur Intel to innovate more?" *Journal of Political Economy*, 119(6), 1141-1200

Gordon, B. (2009) "A Dynamic Model of Consumer Replacement Cycles in the PC Processor Industry," *Marketing Science*, 28(5): 846–8.

Nurski, L. and F. Verboven (2016) "Exclusive Dealing as an Entry Barrier - Evidence from the Car Market," *The Review of Economic Studies*, forthcoming

Moon, Y. E. and Darwall, C. (2005) "Inside Intel Inside," *Harvard Business School Case* 502-083

Prince, J. T. (2008), "Repeat Purchase Amid Rapid Quality Improvement: Structural Estimation of Demand for Personal Computers," *Journal of Economics and Management Strategy* 17(1), 1–33.

Salgado, H. (2008a) "Dynamic Firms Conduct and Market Power: The Computer Processors Industry under Learning-by-Doing," Working Paper, University of California at Berkeley

Salgado, H. (2008b) "Brand Loyalty, Advertising and Demand for Personal Computer Processors: The Intel Inside Effect," Working Paper, University of California at Berkeley

Slade, M. E. (2005) "Product Rivalry with Multiple Strategic Weapons: An Analysis of Price and Advertising Competition," *Journal of Economics & Management Strategy,* 4(3): 445–476

Lafontaine, F. and M. Slade (2008) Exclusive Contracts and Vertical Restraints: Empirical Evidence and Public Policy," in Paolo Buccirossi, ed., Handbook of Antitrust Econonmics, Cambridge: MIT Press, 2008, pp. 391-414.

Song, M. (2007) "Measuring Consumer Welfare in the CPU Market: An Application of the Pure Characteristics Demand Model," *RAND Journal of Economics*, 38, 429-446.

Sovinsky Goeree, Michelle (2008) "Limited Information and Advertising in the US Personal Computer Industry," *Econometrica*, 1017-1074.