Information Technology, Productivity and Asset Ownership: Evidence from Taxicab Fleets*

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We develop a simple model that links the adoption of a productivity-enhancing technology to increased vertical integration and a less skilled workforce. We test the model's key prediction using novel micro data on vehicle ownership patterns from the Economic Census during a period when computerized dispatching systems were first adopted by taxicab firms. Controlling for time-invariant firm-specific effects, firms increase the proportion of taxicabs under fleet-ownership by 12 percent when they adopt new computerized dispatching systems. An instrumental variables analysis suggests that the link between dispatching technology and vertical integration is causal. These findings suggest that increasing a firm's productivity can lead to increased vertical integration, even in the absence of asset specificity.

1. Introduction

This article examines how technology adoption influences firm boundaries and worker skills. Since Coase's (1937) famous observation that firms coordinate transactions internally when doing so is more efficient than coordinating those activities through markets, scholars have sought to explain how firms' boundaries are determined. A large body of empirical evidence now supports the core predictions of transaction cost economics (Williamson 1975, 1985) and property rights theory (Grossman and Hart 1986, Hart and Moore 1990), namely that asset specificity and contractual incompleteness are key determinants of the boundaries of the firm. However, an alternative theory of the firm, initiated by Demsetz (1988), proposes that changes in the productivity of potential trading partners can also influence firm boundaries. This productivity-based theory of integration has received far less empirical support (Jacobides and Hitt 2005), perhaps because the underlying logic has remained informal and imprecise.

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This paper provides a formal productivity-based theory of asset ownership, and tests it by measuring the impact of information technology adoption on asset ownership in the taxicab industry.

In our theoretical model, a firm consists of an asset or a collection of assets (e.g., taxicabs), matched to employees of varying skill, using a particular technology. There are two ways to produce: one relies on skilled labor and little formal control, while the other uses information technology (IT) to coordinate production. Each firm seeks opportunities to produce output using its assets, and our measure of productivity is the probability that the assets are actually utilized. In equilibrium, the model predicts three types of organization: (i) highly skilled autonomous employee-owners; (ii) less-skilled employee-owners who contract with a third-party information technology provider; and (iii) firms that utilize unskilled labor and in-house information technology. The choice among these three modes of organization does not reflect asset specificity or non-contractible *ex ante* investments. Rather, technological capabilities and heterogeneous labor productivity drive both joint-production and vertical integration decisions.

We use the model to analyze forward vertical integration by a supplier whose technology improves. When assets are capacity constrained, as in Levinthal and Wu (2010), concurrent production opportunities are redundant, and the marginal benefits of technology improvements are declining in labor productivity. This observation leads directly to our main prediction: improvements in technology lead to increased integration and a greater reliance on unskilled labor. Intuitively, the technology owner captures more surplus by acquiring assets and using low-skilled workers to produce the final good than by selling an input to skilled third-parties who value it less.

In our empirical application, firms are taxicab fleets, employees are drivers, and the capacity-constrained assets are taxicabs seeking rides. The three types of organization in our theoretical model correspond to: (i) independent owner-operators; (ii) fleet-affiliated drivers who own a car but contract for dispatching; and (iii) shift drivers who rent both a car and dispatching service from a fleet. Our theory predicts that improvements in computerized dispatching technology will lead to increased vertical integration as fleets acquire vehicles from fleet-affiliated drivers who previously used the fleet's dispatching system as a source of referrals. To test these predictions, we use detailed micro data on taxicab firms' vehicle ownership patterns from the Economic Census during a period (1992-1997) when new computerized dispatching systems that greatly improved dispatch times and fleet utilization levels were first widely adopted.[1]

The taxicab industry is an attractive setting to measure the impact of productivity on asset ownership for several reasons. First, production and organizational technologies in this industry are relatively simple, which helps us isolate the impact of a technology-induced productivity change from potential confounding factors, including changes in asset specificity, incentive intensity and monitoring. Second, the returns to adopting new dispatching technology are decreasing in driver ability, which satisfies a key assumption of our theoretical model. High-ability taxicab drivers possess unique knowledge about the spatial and temporal variation in demand within a city,[2] which allows them to be more productive than low-ability drivers.[3] Because a skilled driver's local knowledge reduces his reliance on dispatching, he finds improvements in dispatching technology less valuable. Finally, local taxicab markets are distinct and heterogeneous allowing us to exploit exogenous variation in local market conditions as part of our empirical strategy. In particular, we use population density and the characteristics of other fleets in the same geographic market as instrumental variables that are correlated with the costs and benefits of computerized dispatch systems, but uncorrelated with a focal fleet's asset ownership decisions.

Our empirical results show that adopting a computerized dispatching system causes taxicab firms to increase the percentage of vehicles they own, compared to those they contract for in the open market. Specifically, in a first differences specification that accounts for time-invariant firm heterogeneity, we find that when firms adopt computerized dispatching systems, they increase the proportion of fleet-owned taxicabs by 12% relative to non-adopters. This result is robust to increasingly stringent controls for

[1] Gilbert, Nalevanko and Stone (1993) report that dispatch times fell by 50-60% following the adoption of computerized dispatching, and our own estimates suggest that vehicle utilization increased by 15%-20%.
[2] Woollett, Spiers and Maguire (2009) show that experienced taxicab drivers in London develop a remarkably deep understanding of the spatial structure of the city.
[3] And, indeed, the productivity gap between the most productive and least productive drivers is quite significant. For example, Schaller and Gilbert (1995) report that the top quartile of New York City taxicab drivers earns 59% more than the bottom quartile earns.

endogenous technology adoption, and suggests that by reducing the returns to skilled labor, computerized dispatching technology leads to increased vertical integration in taxicab fleets.

The present study fits into the strategy literature on firm boundaries, and also the economics literature on skill-biased technical change. For the literature on firm boundaries, the paper has two main contributions. First, we develop a model that predicts a systematic relationship between productivity-enhancing technology and the vertical boundary of the firm. Though simple, this model is a first step towards formalizing the intuitive relationship between productivity and firm boundaries discussed by Demsetz (1988) and in the literature on capabilities (Jacobides and Winter 2005).[4] Second, we provide empirical evidence that technology adoption causes firms to increasingly vertically integrate, even without changes in asset specificity.

For the literature on skill-biased technological change, we contribute to the emerging view that information technology adoption does not always increase the relative demand for more skilled labor. Our finding that communication technology complements centralized organization and low worker skill is consistent with recent work by Bloom, Garicano, Sadun, and Van Reenen (2009) and Mahr and Kretschmer (2010). While those papers focus on endogenous skill formation and the span of managerial control, we take skills to be exogenous and emphasize changes in the boundary of the firm. However, all three papers suggest limitations to the standard skill-biased technical change hypothesis that information technology typically increases the demand for skilled labor (e.g. Bresnahan, Brynjolfsson and Hitt 2002, Card and DiNardo 2006).

2. Productivity and firm boundaries

The literature on firm boundaries contains several theories of vertical integration, each offering a different explanation for why firms choose to own a particular set of assets along their production value chain. Transaction cost economics (TCE) suggests that integration reduces the inevitable cost of haggling over

[4] Jacobides and Winter (2005) argue that capabilities, idiosyncratic factors that lead to productivity differences, are the root drivers of vertical integration. One might think of IT and worker skill as capabilities in our model. An alternative generalization of our theory is that we allow technological improvements to substitute for quality-adjusted labor inputs in the firm's production function.

the division of surplus when trading partners are locked into a relationship (Williamson 1975, 1985). Property rights theory (PRT) suggests that ownership provides incentives to make efficient but non-contractible investments (Grossman and Hart 1985). In both TCE and PRT, firms own assets and transact internally when asset specificity—the reduction in the value of an asset between its best and second-best use—is high and market contracts are fraught with hazards.[5]

We develop and test a formal model based on a third branch of the theory of the firm, which proposes that vertical integration will obtain when firms are more efficient at performing key routines or activities compared to their potential trading partners (Demsetz 1988, Langlois 1992, Jacobides and Winter 2005). Specifically, the model describes conditions under which productivity-enhancing information technology adoption induces firms to purchase assets and use unskilled labor to operate them. The key assumption in our model is that capacity-constraints can reduce the total value created by productivity improvements on one side of an arm's length transaction. Thus, to capture the rents produced by improved productivity, a firm must either find unconstrained trading partners (who benefit from the new technology), or integrate to produce a captive source of unconstrained trading opportunities. For example, in our empirical setting, drivers who keep their taxicabs utilized with little assistance from a dispatcher do not benefit from improvements in dispatching technology. And as our theory suggests, taxicab fleets that adopt automated dispatching systems also vertically integrate by acquiring cars and leasing them to unskilled drivers who rely on the dispatcher for rides.[6] The capacity constraints in our model are closely related to the idea of capacity-constrained capabilities in Levinthal and Wu (2010) who invoke the concept to study diversification.[7] We use the same idea to study the joint determination of asset ownership and labor skill.

[5] See Macher and Richman (2008) and Lafontaine and Slade (2007) for a review the empirical literature on transaction cost economics and property rights theory, respectively.
[6] The labor economics literature on de-skilling also suggests that when information technology substitutes for worker skill, IT adoption leads to a lower skilled, or de-skilled, workforce (Autor and Dom 2009).
[7] Levinthal and Wu (2010) distinguish between scale-free resources (e.g., intellectual property) that can be applied without any reduction in utility, and non-scale free resources (e.g., worker-vehicle pairs) that exhibit diminishing returns due to natural physical limits.

2.1 A Model of Productivity, Asset Ownership and Integration

Suppose there are three types of agents: providers of skilled labor, providers of unskilled labor and a firm that supplies a technology.[8] Production requires matching one unit of labor, skilled or unskilled, to an asset (e.g., a taxicab). Assets may be owned by any type of agent and can produce up to one unit of value per period (i.e. one unit of an output whose price is normalized to one). There is a total supply of one unit of assets to be allocated amongst all agents, including the firm.[9] Production is Leontief with respect to capital and labor, meaning that assets and workers are supplied in fixed proportions—one worker for each asset. Thus, technology adoption cannot lead to substitution of capital for labor, though it may alter the mix of skills and relative productivity of employees in the industry.[10]

Given an asset, skilled workers can produce $\theta > 0$ units of output per period with no assistance from the firm. Worker ability (θ) is private information drawn from a uniform distribution on the unit interval.[11] A skilled worker's reservation wage is $w > 0$. There is an inexhaustible supply of unskilled workers, for whom $\theta = 0$ and $w = 0$.

Skilled workers can purchase an asset or rent one from the firm. Moreover, skilled workers who own an asset could work independently or contract with the firm. Thus, our model allows four possible modes of organization (though only three will occur in equilibrium): firm asset ownership (vertical integration) with either skilled or unskilled workers, skilled worker asset ownership with contracting with the firm, or skilled worker asset ownership without contracting with the firm. In the taxicab industry these organizational forms correspond to: fleet ownership of vehicles with either high or low-skill drivers;

[8] Given our empirical application, we call agents that supply labor "workers" though it should be clear that the ideas apply equally if we call them suppliers, contractors or firms, and frame the results in terms of outsourcing rather than the employment relationship. To simplify the exposition we, hereafter, refer to firms that supply productivity enhancing information technology simply as "firms."

[9] All of our main results would hold in a model with an arbitrary number of discrete assets.

[10] If one takes the view that technology is just a special kind of asset, and that labor should be measured in terms of human capital (i.e. adjusted for quality), then there is a capital for labor substitution effect. We discuss this effect in terms of the impact of technology on changes in skills, rather than capital-labor substitution, though both perspectives are potentially instructive.

[11] While the uniform case is easy to analyze, our results generalize to other distributions.

skilled drivers contracting with a fleet for dispatching services, and skilled drivers working independently.

The firm's job is to coordinate the production process. Specifically, access to the firm's technology (dispatching system) increases the productivity of unskilled labor to β units of output per period. Skilled labor can also use the firm's technology to augment their productivity. Specifically, skilled workers generate $\theta + (1-\theta)\beta$ units of output by working with the firm. This function can be derived by assuming that in each period the firm locates opportunities with probability β, and the skilled worker locates opportunities with probability θ, which is independent of β, and because of capacity constraints, no more than one opportunity may be served concurrently.[12] Given this technology, a skilled worker's gross benefit from contracting with the firm (i.e. the gain over independent production before any payments to the firm) equals $(1-\theta)\beta$, which declines with skill. Finally, we assume that the firm's technological resources are scale-free, in the sense that the per-worker benefits of joint production depend on β, but not the number of agents working with the firm.

The model has two periods. Assets are allocated in the first stage according to the following process: (i) the firm offers a (passive) central planner a price *b* for its assets, (ii) workers who wish to purchase an asset for *b* are allocated one, and (iii) the firm is allocated the remaining assets at price *b*. This first stage captures the idea that assets are allocated via a market (in which the firm can set prices) prior to any contracting and production. In the second period, the firm sets one price *p* for contracts with asset owners and a second price *x* for contracts with non-owners, and skilled asset owners decide whether to remain independent, contract with the firm, or exit and take their reservation wage.[13]

[12] An alternative interpretation of our production technology is that $(1-\beta)$ is a measure of coordination costs, as in the knowledge worker model of Bloom et al (2009), so an employee who can work autonomously with probability θ generates total surplus of $\theta + (1-\theta)(1-(1-\beta)) = \theta + (1-\theta)\beta$. More generally, our main results will hold for any technology where the returns to joint production are diminishing in each agent's stand-alone productivity.
[13] Our model makes no assumptions about the firm's location in the value chain. In the taxicab industry, fleets provide dispatching service to drivers who service final demand, so a shift to less skilled non-owner drivers corresponds to "forward" integration. However, the model also applies to a setting where the firm acts as an upstream sales agent who could either refer jobs to independent contractors or "backward integrate" by assigning the same work to in-house employees.

We use backwards induction to solve for sub-game perfect Nash equilibria. To begin, suppose the firm sets prices p and x. A skilled worker who owns an asset will choose to contract with the firm if and only if:

$$\theta + (1-\theta)\beta - p > max\{\theta, w\}.$$

This expression says that collaborating with the firm at price p leaves a skilled worker better-off than his next best option, which is either operating independently or exit. It also implies that skilled asset-owners sort by ability: the most capable workers remain independent, since for them the marginal benefits of accessing the firm's technology are smaller.[14] Lower ability workers contract with the firm, since their assets would otherwise go unutilized more often. This closely mirrors outcomes in our empirical setting, where the highest ability drivers own their own taxicab, but do not contract with a firm for access to their dispatching technology. Less skilled drivers may still own their cab, but choose to contract with a fleet in order to source more rides. The previous expression also implies that the type of skilled worker who is indifferent between contracting and working independently is $\theta^U = (\beta\text{-}p)/\beta$. Thus, firms face a downward sloping demand for referrals to independent asset-owning workers.[15]

Now, consider the first stage of the model. If the firm offers to purchase assets at a price of b, the payoff to a skilled worker (who can also purchase an asset for b) is:

$$max\{\theta\text{-}b, \quad \theta+(1-\theta)\beta\text{–}p\text{–}b, \quad \theta+(1-\theta)\beta\text{-}x, \; w\} \qquad (1)$$

The first term in (1), θ-b, is the payoff from operating independently, the middle terms, $\theta+(1-\theta)\beta$–p–b, and $\theta+(1-\theta)\beta$-x, are the payoffs from contracting with the fleet as an owner and non-owner, respectively, and the final term w is the skilled worker's outside option. Comparing the two middle terms reveals that skilled workers purchase assets and contract with the firm if and only if $p+b<x$. Otherwise, skilled workers prefer the "bundle" (rental plus dispatch) offered to the unskilled. In the technical appendix, we

[14] By a similar argument, skilled workers who do not own an asset will rent one from the firm if and only if $\theta + (1-\theta)\beta - x > w$.

[15] This is where the private information assumption bites. If the firm can use "metering" to charge workers in proportion to their use of the technology, it will set a limit price of $p(\theta) = (1-\theta)\beta$, and will be indifferent between extracting its technology-generated rents through contracting or asset-ownership.

prove, as Lemma 1, that in any sub-game perfect Nash equilibrium $p+b < x=\beta$. Skilled workers never rent assets, and the firm charges the limit price β to unskilled workers.

The intuition behind Lemma 1 is that for any x below β, the firm is better off employing unskilled labor to operate the asset, because $x=\beta$ is the price that leaves unskilled workers on their reservation wage of zero, which is below the skilled workers' opportunity cost. In principle, the fleet could set x above β and rent its assets to skilled workers. If skilled workers anticipate a high rental price, however, they will opt to acquire their own assets, which increases the firm's cost of capital b and lowers the marginal benefits of increasing x. Thus, in equilibrium, the firm is better off setting a low referral price p, to capture the residual demand from skilled owners with underutilized assets, and using unskilled labor to operate any firm-owned assets.[16]

Since skilled workers correctly anticipate $p < \beta\text{-}b$, we can ignore the third term in equation (1) and derive the firm's equilibrium level of asset ownership by comparing the skilled workers' remaining options: independent operation, contracting for referrals and exit. Given p and b, the type of skilled worker who is indifferent between contracting and exit from the industry is $\theta^L = (b+p+w-\beta)/(1-\beta)$. Thus, as long as $\theta^L < \theta^U$ the firm will own a share of assets $S(b)=\theta^L$ and sell referrals to a share of independent asset-owning workers $D(p,b)= \theta^U - \theta^L$. When $\theta^L > \theta^U$, there is no demand for contracting, so $D(p,b)=0$, and the firm's share of assets is determined by the type of skilled worker who is indifferent between exit and operating independently, specifically $S(b)=b+w$. The firm's *ex ante* profits are, therefore:

$$\Pi(p,b) = D(p,b)\, p + S(b)[\beta - b],$$

[16] Lemma 1 implies that the firm will be indifferent between two ways of organizing its supply chain: it could charge unskilled workers $x = \beta$ and allow them to service final demand, or hire unskilled workers at w=0 sell the output of β itself. While the former arrangement (asset rental) is typical in the taxicab industry, readers may find it more intuitive to think of a value chain where the firm as located "between" workers and final demand. In that case, high-skilled worker might be said to disintermediate the firm.

where the first term in $\Pi(p,b)$ comes from contracting to provide skilled asset owners with referrals, and the second term is derived from operating firm-owned assets.[17] In the appendix, we solve for the optimal prices and the resulting allocation of assets. Our main results are illustrated in Figure 1.

INSERT FIGURE 1 ABOUT HERE

Each point on the horizontal axis of Figure 1 corresponds to a different equilibrium, with the allocation of assets for that equilibrium depicted on the vertical axis. The figure shows that when $\beta<(1-w)$, for example at the point β_0, the highest skilled workers produces more surplus than an unskilled worker operating the firm's technology, and the firm sets $p^* = \beta/2$ and $b^* = (\beta-w)/2$, which leads to $\theta^U = ½$ and $\theta^L = w/[2(1-\beta)]$. Thus, the three equilibrium modes of organization allowed by our model—centralized production with unskilled labor (vertical integration), contracting between skilled workers and the firm (joint production), and independent asset-ownership by skilled workers—will co-exist. If skilled and unskilled workers have the same outside option (w=0), we have $\theta^L=0$, and centralized production disappears. Alternatively, when the firm's technology outperforms the highest skilled worker, so $\beta >(1-w)$, the firm sets $b^* = (\beta-w)/2$ and owns $(\beta+w)/2$ percent of all assets. In this case, skilled workers cease to contract with firms and there is a sharp transition between firm and worker-controlled production.

When $\beta < (1-w)$ the margin between contracting for referrals and firm asset ownership is nonlinear, specifically θ^L is a convex function of β, because the firm faces a trade-off between asset purchases (raising b) and contracting (raising p) as a mechanism for capturing the value from their technology. The trade-off between vertical integration and joint production only emerges when the benefits of joint production are decreasing in worker ability (e.g. because of a capacity constraint), since the firm could otherwise hold $D(p,b)$ constant by raising the asset price b and referral price p at exactly the same rate. Moreover, the trade-off between vertical integration and joint production disappears when $\beta >(1-w)$, since

[17]The main predictions will go through as long as the demand for contracting $D(p,b)$ declines with p, and the supply of assets $S(b)$ increases with b. For example, these assumptions will hold in an oligopoly model where firms with identical productivity are horizontally differentiated (e.g., geographically).

in that case there is no skilled-worker demand for referrals at the equilibrium asset price b^*. This last result can be seen in Figure 1, where the margin between firm and worker ownership becomes linear in β.

Our main hypothesis summarizes the key comparative static result of the model by describing how asset ownership changes with a shift in the relative productivity of the firm's technology, which corresponds to a move along the horizontal axis in Figure 1:

> *HYPOTHESIS 1: If a worker's skill level is private information and the marginal benefits of technology adoption are decreasing in worker skill, than an increase in firm productivity from adopting the new technology will lead to an increase in vertical integration (asset ownership).*

Intuitively, increasing β raises the price the firm can charge unskilled labor, which raises the firm's willingness to pay for assets. Asset purchases drive out the least capable of the skilled workers. When β is small enough, it remains efficient to partner with some low-skilled workers to improve their utilization. However, the firm contracts less with skilled workers as β grows because the remaining skilled workers are highly productive when working independently, and therefore, have less excess capacity. Thus, whenever there is joint production *ex ante*, and the other key conditions of the model are met, adoption of productivity enhancing information technology unambiguously leads to increased vertical integration and de-skilling within the firm.

Before turning to the details of our empirical setting, we offer a few remarks about the theory. First, in contrast to TCE and PRT (Williamson 1975, 1985; Grossman and Hart 1986, Hart and Moore 1990), which assume that a firm's production technology is fixed and hypothesize about the correlation between vertical integration and changes in asset specificity, we assume that asset specificity in an exchange relationship is fixed (or at least uncorrelated with changes in production technology) and hypothesize that there is a positive correlation between productivity and vertical integration. By separating the effects of productivity from transaction costs, we make a clear prediction about the conditions under which productivity enhancing information technology adoption leads to increased firm asset ownership. Second, several features of the model are not stated formally, as hypotheses to be tested, but are nevertheless consistent with the institutional realities of our empirical setting. In particular, Lemma 1 predicts that the price of renting assets *x* will be large compared to the price of contracting for referrals *p* (as can be seen in the 1992-1997 TLPA fact books). The model also predicts that for certain parameter values, independent owner operators, fleet-affiliated owner operators and low-skilled shift drivers can co-exist—a situation we describe at length below. Finally, we note that it is a fairly short step from this theory of productivity and vertical integration to a related theory of capabilities and vertical integration. While the productivity enhancing technology in our model need not have the defining features of a capability (i.e. an inimitable, firm-specific, routine-based source of competitive advantage), one could replace the generic, exogenously determined, technology in our model with a firm-specific capability that endogenously improves productivity relative to other firms. Thus, we could derive a model of capabilities and vertical integration by adding a firm subscript to the parameter β. However, this interpretation raises deeper questions that our model does not address, notably whether joint production inevitably leads to relationship specificity in settings where β is rooted in firm-specific processes and routines, an idea discussed in more detail by Argyres and Zenger (2011).

3. Empirical setting: the taxicab industry

While taxicab fleets began using computers during the 1970s, data dispatch systems did not arrive until the early 1980s. By the early 1990s, firms began adopting modern computerized dispatching systems, comprised of a central computer that coordinates vehicles and communicates information to vehicle-level on-board computers. Basic computerized dispatching systems, often called "partially automated" systems, require drivers to manually send a signal to the central computer, indicating their location by entering a zone number into a simple onboard computer, and human dispatchers to announce ride allocations, using a separate communication system (usually a radio). More advanced "fully automated" systems deploy in-car devices with two-way communication capability, allowing a back-end optimization algorithm to communicate directly with onboard computers in taxicabs. These systems also automatically monitor pickup and drop-off actions, such as turning the meter on and off. During the sample period, fixed costs associated with fully automated systems were around $750,000, while per vehicle costs were about $1,000-$2,000, including the onboard computer (Gilbert, Nalevanko and Stone 1993). The most advanced computerized dispatching systems are GPS-based, which eliminate the need for drivers to enter zone numbers and track a vehicle's exact location at all times.[18]

Historically, some taxicab firms were organized around relatively sophisticated radio-based dispatching systems, while other taxicab firms often had rudimentary dispatching systems, sometimes as basic as hand-written notes on a bulletin board. Firms with more advanced dispatching systems usually owned most or all of their taxicabs and used their dispatching systems to support a network of inexperienced shift drivers, who were typically non-owners. At the same time, firms with simple, low-cost dispatching systems catered to experienced owner-operators who managed their own block of business but banded together, often as cooperatives or associations, primarily to share maintenance and administrative costs.

In addition to non-owner drivers and owner-operators who contract with firms for shared services, there is a third type of driver: independent owner-operators, typically very experienced drivers who choose to operate without any firm affiliation or support. Driving independently represents owner-operators' outside option when they contract with fleets, as owner-operators are free to switch between being independent and working for firms.[19]

Because the use of the on-board computer component of the dispatching system is relatively inexpensive, and, is readily contractible in arms-length exchange, it is unlikely that changes in asset specificity are an important driver of changes in firm boundaries in our context. Furthermore, the advent of computerized dispatching did not produce large changes in incentive intensity or monitoring. Taxicab

[18] Estimates of the cost of partially automated systems vary widely based on the functionality of the system. The most basic systems probably cost about half as much as a fully automated system. GPS-based systems are substantially more expensive than partially and fully automated systems.

[19] The U.S. taxicab industry was buffeted by two major shocks during the mid-1990s. The first, the subject of this paper, was technological as new computerized dispatching systems reached the taxicab market. The second shock, a regulatory change, led to widespread diversification into limousines decreased vertical integration as formerly independent driver-owners increasingly contracted with firms (Rawley and Simcoe 2010). The net effect of the two shocks was a secular decline in vertical integration levels between 1992 and 1997. In this paper, we investigate the effects of computerized dispatching on asset ownership, controlling for the effect of diversification.

drivers are almost always full residual claimants who pay a fixed fee to the firm and keep all of the gross revenue from their activities; even if they do not own the taxicab they drive (Schaller and Gilbert 1995).

There are two reasons for the ubiquitous use of high-powered incentives in the taxicab industry: monitoring costs and legal issues. In most markets, taxicab drivers both fulfill pre-arranged rides and search independently for spot market hails, and firms believe that it is more efficient to give drivers broad freedoms to drive as they wish along with strong incentives to locate rides independently. Furthermore, compensating drivers with high-powered incentives allows firms to maintain drivers as independent contractors, as opposed to formally employing them, which has significant payroll tax advantages. Given these two reasons for deploying high-powered incentives, and the fact that monitoring drivers requires at least some costly interventions, the system of combining high-powered incentives with limited monitoring persists to this day, even though more advanced GPS-based dispatching systems ostensibly allow for greater levels of monitoring.[20] Because high-powered incentive contracts are nearly ubiquitous and monitoring efforts circumscribed in the taxicab industry, our empirical analysis can effectively measure the impact of an IT-induced productivity change without contamination from the incentive and monitoring effects that are important in other settings (e.g. Brynjolfsson 1994, Baker and Hubbard 2004).

Our theory predicts that more capable drivers should own their vehicles, and anecdotal evidence from the taxicab industry supports this proposition. Interviews with fleet managers and taxicab drivers suggest that owner-operators are more professional, speak better English, and are able to source more of their own rides than the low-skilled "shift" drivers who possess only a hack license, and are frequently newly arrived immigrants. Quantitative evidence is also consistent with our model. For example, Bruno (2010) reports that driver-owners earned 37% more than non-owner shift drivers in Chicago in 2008. Experienced drivers are far more productive than inexperienced drivers primarily because they develop a deep understanding of demand patterns in their markets. While inexperienced drivers tend to inefficiently

[20] Our interviews with firms and drivers confirmed that taxicab drivers were almost always full residual claimants during our sample period. This practice persists to this day. For example, see Bruno (2010) for a detailed analysis of contracting behavior in the Chicago market.

chase rides, experienced drivers know where to go and, importantly, when to wait for rides to materialize without wasting time and gasoline driving around the city.

Because they are less likely to source their own rides, low-skilled shift drivers are often the greatest beneficiaries of improved dispatching technology. Relative to radio dispatching, computerized dispatching levels the playing field by more efficiently allocating vehicles to rides (Gilbert, Nalevanko and Stone 1993). Inexperienced drivers enter pre-assigned high-volume zones and wait in an orderly (virtual) queue until they are assigned a ride, leading to significantly improved utilization at lower cost. On the other hand, computerized dispatching is much less valuable for experienced drivers because they do not depend on an efficient dispatching system to operate at close to full capacity—they already know where to go to find rides. Thus, the benefits of computerized dispatching are disproportionately gained by inexperienced drivers.

Another important institutional feature of the taxicab industry, especially for this study, is the unique local regulatory, competitive and geographic factors that influence the costs and benefits of computerized dispatching systems. Local regulations determine retail prices, fix the number of permits or medallions, devise a permit allocation system, limit the transferability of permits, set restrictions on the entry and exit of fleets and may require either fleets or individuals to own operating permits. Moreover, the geography of a city can influence the distribution of rides between dispatched fares and curbside hails. Most of these factors are exogenous to a fleet's choice of dispatching technology, and therefore provide the natural experiment missing from many studies of technology adoption and firm boundaries. Furthermore, we exploit between-market variation in population density and taxicab ownership rates to construct instrumental variables for a fleet's endogenous decision to adopt computerized dispatching technology.

Since the full functionality of onboard computers installed in taxicabs is sometimes specific to the firm's dispatching system, transaction cost economics' asset specificity mechanism represents a leading alternative hypothesis to our theory of vertical integration in response to a productivity boost from information technology adoption. The nature of asset specificity is often context dependent and subtle, which means that it must be considered carefully. However, both data and interviews suggest that contractual hazards are not severe with respect to contracting over the installation and use of onboard computers in the taxicab industry. It is certainly apparent in the data that many firms deploy onboard computers in owner-operator vehicles. On average, 31% of vehicles are owner-operator taxicabs in firms that use computerized dispatching (see Figure 2). The fact that the contracting through market exchange to deploy onboard computers in owner-operator vehicles is widespread indicates that such contracts are not particularly fraught with hazards. Industry interviews confirm that firms often recoup their dispatching investment costs by levying a surcharge on owner-operators for their use of the system.

4. Empirical strategy

4.1 Data

Data on taxicab ownership come from the 1992 and 1997 Economic Censuses. This comprehensive dataset records every taxicab firm in the United States (SIC code 412100) with at least one employee. Economic Census micro-data is extremely valuable because it includes the number of taxicabs by ownership type (e.g., fleet-owned versus driver-owned), allowing for an unusually precise measure of within-firm changes in vertical integration over time. The census records 3,184 taxicab firms in 1992 and 3,337 taxicab firms in 1997. Of this population, 787 firms are "substantial entities" that had at least $10,000 of taxicab revenue and two taxicabs, and maintained operations during in both 1992 and 1997.

Because the Economic Census does not contain information on dispatching technology, we use two additional sources of data on the adoption of computerized dispatching.[21] The first source of dispatching data is a detailed survey conducted in 1998 by the Transit Cooperative Research Program (TCRP).[22] We augment the TCRP data with information from our own mail survey, conducted in 2005, of all taxicab operators in the Dun and Bradstreet (D&B) business register with taxicab SIC code 412100 and at least

[21] We also conducted a number of interviews with city taxicab regulators, fleet owners and dispatching technology vendors and taxicab drivers, which provided a wealth of insights that greatly improved this paper. For so freely sharing with us the knowledge they have accumulated regarding the U.S. taxicab industry, we are particularly indebted to C.J. Christina, Thomas Drischler, Stan Faulwetter, Alfred La Gasse, John Hamilton, Marco Henry, Kimberly Lewis, Aubby Sherman, and, especially, Craig Leisy.

[22] We are grateful to Tom Cook and Gorman Gilbert for generously sharing the detailed responses to the TCRP survey with us. The TCRP survey was conducted during 1997.

two employees.[23] Our survey was addressed to the principal owner of the firm on record with D&B and asked six questions about the firm's current and past dispatching systems (type and year of adoption) as well as five additional questions about the firm's vertical and horizontal scope, age, and regulatory environment.[24] We merged the resulting 635 (363 TCRP observations and 272 author survey observations) observations with the 3,153 observations in the 1997 Economic Census by zip code or county code and firm size. The merging process generated 409 unique matched observations, 197 from the TCRP survey and 212 from the authors' survey.[25] Of the 409 matched observations, 244 operated continuously between 1992 and 1997 and reported valid data in both years to the Economic Census, representing 31% of all substantial entities.

Table 1 describes our key variables and Table 2 shows summary statistics for the firms in the sample used for our empirical tests (n=244) and for all firms that meet our sampling criteria in 1992 or 1997, including firms that entered or exited the industry between 1992 and 1997. Thirty-six percent of the taxicab firms in the test sample adopted computerized dispatching between 1992 and 1997. The average firm in our sample had 52 taxicabs in 1992, 89% of which were owned, compared to an average fleet size of 19 taxicabs with 82% owned in the full set of substantial entities in the Economic Census. By 1997, the average firm in our sample had grown to 67 taxicabs (65% owned), compared to an average fleet size of 27 taxicabs (61% owned) for the entire Census. Our test sample contains 63% and 55% of all taxicabs in US fleets in 1992 and 1997, respectively. While this sample contains a significant proportion of the substantial entities in the industry, larger firms are clearly oversampled. Because we are interested in estimating the effect of dispatching technology adoption on the set of firms at risk to adopt, not necessarily the population average treatment effect of computerized dispatching adoption for all taxicab

[23] The author survey generated a 26% response rate. We thank Peter Thompson for providing us with a file that allowed us to match zip codes from D&B to county codes used in the Economic Census.

[24] Both the TCRP and author surveys inquire whether firms use radio dispatch, GPS-based systems, "fully automated computerized systems", or "partially computerized" systems. For the purposes of this study we treat the three types of computerized dispatching systems identically (less than 5% of respondents used GPS during the sample period). The TCRP survey asked about concurrent use of computerized dispatch, while the author's survey inquired about current and past use of computerized dispatching systems.

[25] The 226 unmatched observations were primarily small firms. Small firms are more difficult to match by zip code or county code because there are often many small firms in the same area.

firms, it is reasonable to focus on a sample of larger substantial entities. While non-response bias remains a threat, a series of robustness checks suggest that it does not influence our results.

Table 3 shows the size distribution of firms in our empirical tests in 1992, and the percentage of firms that adopted computerized dispatching between 1992 and 1997, according to the firm's 1992 size category. As expected, the smallest firms, those with exactly two taxicabs, never adopt computerized dispatching technology, while 70% of fleets with over fifty or more taxicabs in 1992 adopted computerized dispatching systems by 1997. The rate for the largest size category is approximately three times the rate of firms with less than 25 taxicabs (23% adoption rate), which supports our contention that large firms are more likely to adopt computerized dispatching systems.

Figure 2 illustrates the secular decline in vertical integration in taxicab firms and previews our main result, showing changes in vertical integration levels for the "treated" firms that adopted computerized dispatching systems during that time period, and the "control" that did not. In 1992, the 87 IT-adopting firms owned 86% of their vehicles, while the 157 firms that did not adopt computerized dispatching owned 91% of their vehicles. By 1997, after the secular decline in levels of vertical integration, the adopters owned 69% of their vehicles (a drop of 17%), while the non-adopters owned 62% of their vehicles (a decrease of 29%). Thus, net of the secular decline in vertical integration, firms that adopted computerized dispatching systems increased their level of vertical integration by 12% relative to firms that did not adopt. In the statistical tests that follow, we show that these summary statistics closely approximate the relationship between computerized dispatch adoption and average changes in asset ownership after controlling for observables and allowing for endogenous technology adoption.

INSERT FIGURE 2 ABOUT HERE

4.2 Empirical specification

To measure the impact of computerized dispatching systems on changes in vertical integration, we run cross-sectional regressions in first differences using the change in the share of vehicles owned by fleet *i* ($\Delta FOWN_i$), which is continuous and bounded between negative one and one, and a binary explanatory variable $\Delta TECH_i$ that equals one if the firm adopts computerized dispatching technology and zero otherwise, as in OLS equation:

$$\Delta FOWN_i = \alpha + \Delta TECH_i\ \boldsymbol{\phi} + \boldsymbol{X_i}\,\theta + \varepsilon_i \qquad (2)$$

The cross-sectional first-differences specification in equation (2) is similar to using firm and time fixed effects when there are only two periods of observation. In particular, the parameter α measures the average change in fleet ownership rates for non-adopters and $\boldsymbol{\phi}$ measures the difference in fleet-ownership changes between IT adopters and non-adopters (i.e. it is a difference-in-differences estimator). Estimating the model in first-differences within fleets controls for time-invariant firm-specific heterogeneity without biasing the estimated standard errors downward, allowing us to conservatively cluster our standard errors at the market (county) level.

Following Rawley and Simcoe's (2010)[26] work on vertical integration in taxicab fleets we include a set of exogenous control variables $\boldsymbol{X_i}$ that could plausibly shift the boundary of the firm. The controls include changes in firm size (logged number of vehicles) to capture scale effects; changes in horizontal scope, measured by log limousine capital and log limousine capital squared;[27] changes in the level of vertical integration of other fleets in the same market, to control for time varying market-level drivers of vertical integration; and changes in the number of taxicabs and limousines under management operated by competing fleets in the same market (county)—a proxy for the competitive dynamics of the firm's operating environment.

In the ideal experiment, one would randomly assign computerized dispatching to firms and observe how their asset ownership patterns changed relative to firms who were not assigned the technology.

[26] Rawley and Simcoe (2010) present two specifications in their paper on changes in vertical integration in taxicab firms. We follow the empirical model used in their fixed effects model with one additional control—change in log taxicab capital squared—though we do so using a cross-sectional regression in first differences. The first differences model $\Delta Y_i = \alpha + \Delta \boldsymbol{X_i}\beta + \varepsilon_i$, closely approximates the fixed effect model $Y_{it} = a + \lambda_i + T_t + \boldsymbol{X_{it}}\beta + e_{it}$. The results are robust to specification and to excluding the change in log taxicab capital squared.

[27] Rawley and Simcoe (2010) show that diversification influences vertical integration in taxicab fleets due to diseconomies of scope between limousine and taxicab operations. They focus on diversification as a binary event (i.e., whether firms diversify or not). We include continuous measures of diversification, though our results are robust to controlling for diversification with a dummy variable.

However, the decision to adopt computerized dispatching is an endogenous choice that may be influenced by unobserved firm-specific factors that are also correlated with changes in asset ownership. Even OLS specifications that control for time-invariant firm characteristics and changes in firm size may not identify the causal impact of computerized dispatching on asset ownership because the benefits of computerized dispatching vary based on unobservable (to the analyst) firm and market characteristics that may also be correlated with asset ownership decisions. We address the potential for endogeneity in the technology adoption decision using propensity score matching to control for observable differences between firms[28] and instrumental variables (IV) to control for selection on unobservables.

The main concern with our OLS first-differences specification is that, even after balancing on the propensity score, fleets may adopt computerized dispatching because of unobserved factors that raise the returns to *both* IT adoption and vertical integration. These omitted variables would lead us to overestimate the causal impact of computerized dispatch adoption on fleet asset ownership. We exploit the fact that taxicab fleets in our sample operate in hundreds of distinct local markets to construct instrumental variables that are correlated with the adoption of dispatching technology and (by assumption) uncorrelated with unobserved factors that influence the level of vertical integration.[29]

Our first IV is population density, which enters the first-stage flexibly as logged population (*POP*) and land area ($MILES^2$). Greater population density increases the returns to adopting computerized dispatching technology because the complexity of taxicab operations tends to increase in markets where optimally matching vehicles to rides is contingent on where and when other rides terminate. And since population density is clearly predetermined, it should be uncorrelated with factors that shift the returns to fleet asset ownership.

[28] As in Rosenbaum and Rubin (1983), we calculate the propensity score of the probability of adopting computerized dispatching systems, and then drop firms off the common support of the propensity score distribution. We also weight included firms by the inverse probability of being treated (Imbens 2004). Complete first-stage results are available from the authors. As expected, the most important single factor influencing adoption was the (log) number of taxicabs in the firm in 1992.

[29] Because the 244 fleets in our panel operate in 173 different local markets, we are not concerned that the instrument will fail to generate sufficient variation in the first stage.

Our second IV is the lagged (1992) average fleet size of other firms in the same market (*AVGTAXIS*). Lagged size of other fleets in the same market, *AVGTAXIS*, should not cause changes in firm asset ownership, particularly when controlling for the firm's time invariant characteristics as well as the change in the firm's own size. However, lagged average size of other fleets in the same market may be correlated with a firm's adoption of a computerized dispatching system to the extent that the firm is operating in a market where supply and demand, or regulatory characteristics of the market, tend to exogenously increase the average size of firms.

An ideal instrumental variable would generate fleet-level variation in the incentives to adopt computerized dispatching, thereby allowing us to control for market-specific trends in asset ownership. Unfortunately, we could not identify any fleet-level instruments, so our identification strategy is vulnerable to omitted variables that are correlated with both our market-level instruments and firm-level changes in asset ownership. In particular, one may be concerned that independent owner-operators are more likely to contract with fleets in markets where *AVGTAXIS* is larger. However, we expect any resulting bias to be small since our specification controls for time-invariant firm-specific factors and a number of time-varying observables at both the firm and market level.

5. Results

We test the hypothesis that adopting productivity-enhancing technology leads to increased vertical integration and a less skilled workforce by running within-fleet regressions of changes in asset ownership on the adoption of computerized dispatching systems. Table 4 shows the results of tests on the survey respondent set with no controls. Column 1 reports estimates from a simple OLS specification. We find a strong partial correlation between IT adoption and increases in vertical integration. Specifically, the share of fleet-owned vehicles increased by 13% in firms that adopted computerized dispatching systems compared to those that did not adopt. The large negative coefficient on the constant term (α) reflects the secular trend towards dis-integration apparent in Figure 2. Column 2 in Table 4 shows results of the same model after matching and weighting by the propensity score to control for observable differences between adopting and non-adopting fleets. While the broad shift towards vertical dis-integration becomes more pronounced in this specification, there is no change in the estimated impact of computerized dispatch adoption on fleet asset ownership.

While OLS and propensity score matched estimates are approximately equal to the raw difference-in-differences shown in Figure 2, the size of our estimated effect increases substantially when we instrument for the fleet's adoption decision (column 3). The lower part of column 3 shows that the instruments are strong statistically, with an F-statistic of 8.2 and statistically significant t-statistics on two of the three instruments in the first stage of the 2SLS model. The top part of column 3 reports the second stage estimates from our 2SLS procedure, which are more than three times larger than the estimates in columns 1 and 2. Although our 2SLS estimates are much noisier than the OLS and propensity score matched parameter estimates, the differences in coefficients is statistically significant at the 10% level. The interpretation of the 2SLS result is that if computerized dispatching technology adoption were randomly assigned, the impact of $\Delta TECH$ on firm asset ownership would be larger than at firms that do (endogenously) adopt the technology. Thus, if the 2SLS instruments are valid, the endogenous adoption of computerized dispatching biases the true impact of adoption on asset ownership toward zero. Comparing the OLS and 2SLS results suggest that IT adopters in dense cities with large taxi fleets remained more integrated than a typical fleet that adopts computerized dispatching. One possible explanation for this finding is that large dense cities have a more competitive pool of low-skilled labor to draw on for operating fleet-owned vehicles.

Since we have more instruments than endogenous variables, it is possible to conduct a test of over-identifying restrictions using Sargan's J statistic. The over-identification test weakly rejects the null hypothesis that all of our instruments are valid ($p<0.10$), suggesting that the three IV's used in our model produce rather different point estimates of the treatment effect. To test the robustness of our results, particularly for the IV specification, we add a number of firm and market level controls. These results are presented in Table 5.

Table 5 shows that several controls do appear to influence vertical integration. As in Rawley and Simcoe (2010), we find that increasing diversification into limousines (*Δlog limousine capital*) leads to decreased vertical integration because firms replace non-owner taxicab drivers with more professional owner-operators to manage diseconomies of scope. Also, when firms grow their taxicab business quickly (which we control for with (*Δlog taxicab capital)*^{2}), they rely more heavily on attracting owner-operators, which leads to lower levels of firm ownership of taxicabs. While the inclusion of controls explains a much larger proportion of the variance of changes in asset ownership (the R^2 jumps from 0.03 to 0.20 in the OLS specification), the magnitude and statistical significance of our main results are unchanged relative to Table 4.

With controls, the 2SLS estimate of the impact of computerized dispatching technology on asset ownership is large and statistically significant, but the difference between the 2SLS and OLS point estimates ceases to be statistically significant. Unfortunately, we cannot be certain whether the lack of statistical significance on the difference in the coefficients is a result of effectively controlling for sources of firm-specific heterogeneity in our OLS specification, or if the result is being driven by noise in the 2SLS estimate. The Durbin-Wu-Hausman test for the necessity of the instruments, in the presence of the full set of controls, was equivocal as it did not reject the hypothesis that the instruments are necessary only at the 10% level. A more pressing concern is that an F-statistic of 4.0 in first stage may indicate that the second stage results are being spuriously generated by the many weak instruments problem. To verify that the 2SLS results are not being driven by the many weak instruments problem, we re-estimated the 2SLS models using only our main instrument—lagged average size of other firms in the same market—and found the magnitude of the 2SLS estimates to be even larger (though noisier) and still statistically significant at the 5% level.

We use two robustness checks to verify that our results are not being driven by non-response bias. First, since fleet-size is positively correlated with both response rates and computerized dispatch adoption, we tried treating all non-respondents as non-adopters and ran the OLS regressions on the full sample (including a dummy to indicate unmatched firms). We obtained nearly identical estimates to our original OLS specification, suggesting that the effect of excluding the unmatched firms from our main analysis does not bias the results. Second, we re-ran all of our models (both with and without the non-respondents) using a sample that excludes small firms, using different definitions of small (e.g., more than 5 taxicabs, 10 taxicabs, 20 taxicabs). These models also produce similar, though progressively nosier, results as with the larger set. These robustness checks strongly suggest that our results are not driven by non-response bias in the collection of survey data.

Taken together, the empirical results show that the adoption of computerized dispatching leads to (at least) a 12-14% increase in fleet ownership of taxicabs.[30] This finding supports the paper's core hypothesis that when workers have private information about their own ability, and the returns to technology adoption are decreasing in worker ability, adoption of a productivity-enhancing technology will be accompanied by increasing firm asset ownership and a reduction in skilled labor use.

6. Conclusion

This paper develops and tests a simple formal model that demonstrates how changes in productivity can alter firm boundaries and employee skills. In particular, if high-skilled workers realize lower benefits from adopting a productivity-enhancing information technology (e.g. because of capacity constraints), then technology adoption leads to increased vertical integration and de-skilling within the firm. Though simple, the model represents an important first step towards formalizing the relationship between productivity and firm boundaries that lies at the heart of the literature on capabilities and vertical integration (Jacobides and Winter 2005). We test the model's core prediction using data on the adoption of computerized dispatching systems in taxicab firms. Taxicab firms that adopt computerized dispatching between 1992 and 1997 increased their share of fleet-owned vehicles by 12% relative to non-adopters over the same time period. This result is robust to controls for endogenous technology adoption suggesting that technology induced changes in productivity lead to changes in firm boundaries in a predictable manner, even in the absence of non-contractible changes in asset specificity.

Though we identify conditions under which information technology adoption leads to increased vertical integration, and show that our particular empirical context fits well with these conditions, our results may not generalize well to other settings. In particular, a key necessary condition for the results in

[30] All of the results are qualitatively the same in a Tobit specification.

our formal model is that the marginal benefits of information technology adoption are diminishing with worker ability. Building on Levinthal and Wu (2010), we motivated this assumption in terms of capacity constrained resources; its validity in other contexts will depend on the particulars of the institutional setting. A second limitation of our study is that we have little to say about the origins of heterogeneous worker ability. We treat each worker's skill as an exogenous endowment, akin to natural ability. Expanding upon the model to endogenize worker ability, perhaps as knowledge gained as the outcome of a learning process, would be an interesting extension of our model, but is beyond the scope of this study.

This article exploits a unique empirical setting to make credible causal inferences about the impact of technology adoption on vertical integration. However, the idiosyncrasies of the taxicab industry should not cloud the general applicability of our conceptual approach to a broad range of firms and industries. Indeed, at least since Demsetz (1988) scholars have long suspected that heterogeneity in productive capabilities can explain vertical integration in any industry. What our model highlights that has been missing from informal characterizations of heterogeneous productivity and firm boundaries is the crucial role non-skill-biased technical change can play in driving vertical integration decisions. In particular, our analysis demonstrates the importance of understanding the interplay between technological change and worker skills when studying firm boundary decisions. To see the generality of this idea, consider Rochlin's (1997) account of the rise of the vertically integrated firm at the end of the second industrial revolution, which describes how a great wave of technological improvement squeezed out autonomous craft suppliers working with their own tools in favor of a lower-skilled employee workforce who produced outputs using firm-owned assets. More recently, in the context of analyzing the Zara Corporation, Gallaugher (2008) notes the connection between improved information technologies, lower skilled labor and vertically integrated manufacturing.[31] While we do not claim that our model is universal, the qualitative results in Rochlin (1997) and Gallaugher (2008) hint at its broad applicability to settings outside the taxicab industry.

[31] Zara uses information technology to dramatically reduce design to delivery cycle time, but to implement its information technology system the firm eschews high-end outside designers and textile producers in favor of vertically integrated production designed by employees "fresh from design school" (p.4).

This article also closes a gap between intuition and theory in the existing literature, by providing a simple testable framework for evaluating the impact of productivity enhancements on vertical integration. In terms of the workhorse model of vertical integration, transaction cost economics, a key insight from our model is that by allowing the firm's production technology to vary exogenously, while holding asset specificity constant (instead of making the traditional assumption that the firm's productive capacity remains fixed while allowing asset specificity to vary exogenously), one can generate clear predictions about the link between productivity and vertical integration. Our key empirical finding provides large-sample evidence of a causal relationship between productivity enhancing information technology adoption and the boundary of the firm. By delivering a well-identified empirical result, this research lends credence to prior work on productivity and vertical integration (Jacobides and Hitt 2005). Methodologically, this study points to the opportunities inherent in exploiting exogenous local market variation in localized industries to identify the causal effects of organizational strategies. Empirical research in strategy is increasingly concerned with identification (Hamilton and Nickerson 2003), and localized industries offer tremendous potential for generating empirical tests that control for the endogeneity of organizational choices.

For practitioners, this research suggests an opportunity for forward-looking managers to anticipate the impact of information technology adoption decisions on the organization of the firm. Managing vertical integration and the boundary of the firm is one of the cornerstones of corporate strategy. We show how corporate managers can anticipate the implications of productivity enhancing information technology on the vertical scope of the firm.

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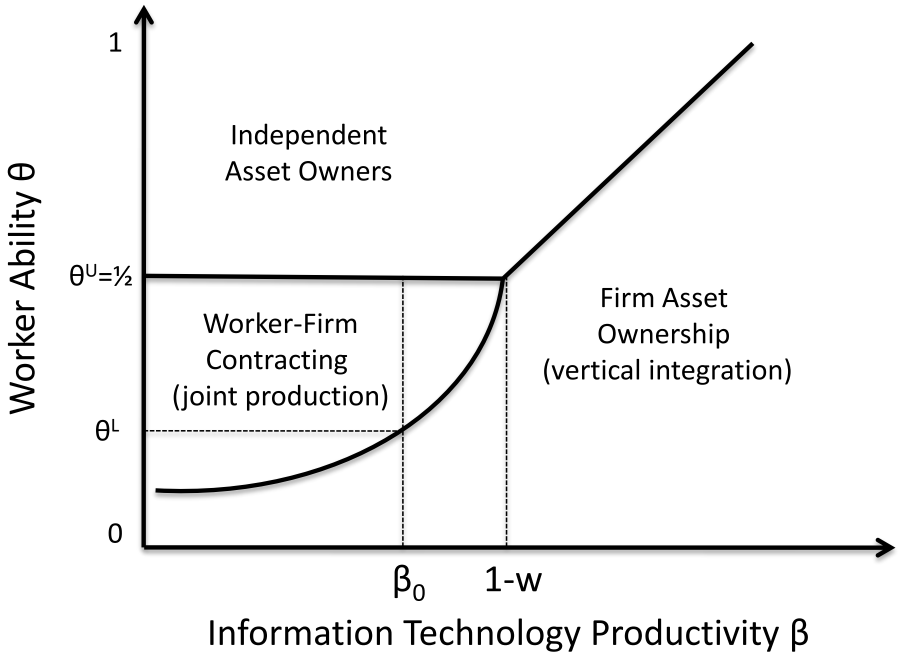
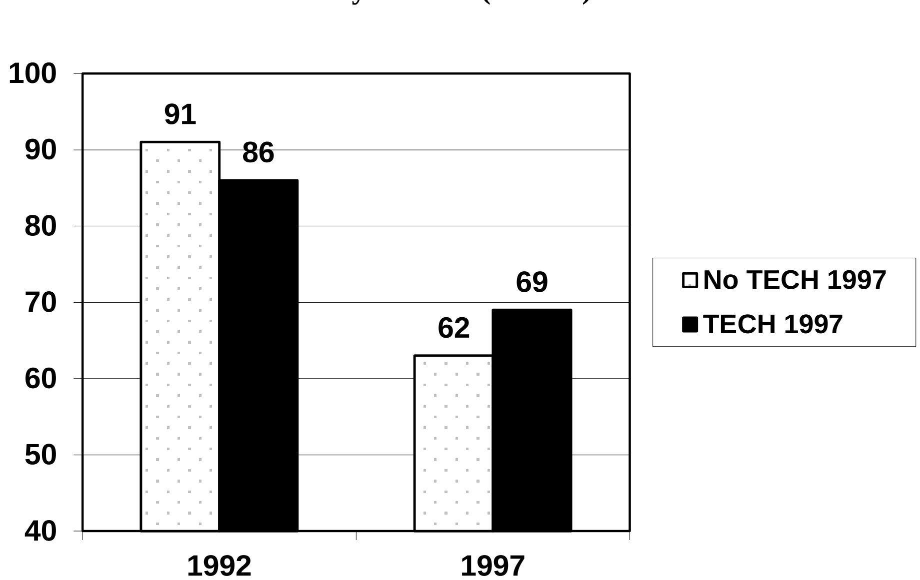
Figure 1 Firm productivity, worker ability and asset ownership



The figure illustrates the equilibrium level of asset ownership in an industry given worker ability and any given level of firm productivity. For example at β_0, workers with ability between θ_0^L and θ^U will acquire assets and contract with the firm for the right to use their productive technology. When firm productivity improves, some of these workers will sell their assets to the firm and exit the industry.

Figure 2 Extent of vertical integration before and after adoption of computerized dispatching technology



TECH 1997 (black bar) refers to firms that adopt computerized dispatching technology between 1992 and 199, while No TECH 1997 (light bar) refers to firms that do not adopt computerized dispatching technology between 1992 and 1997.

Table 1: Variable descriptions

Variable name	Level of variation	Purpose	Description
Dependent and explanatory variables			
ΔFOWN	Firm	Dependent variable measuring the extent of firm vertical integration	Percentage change in the proportion of taxicabs in the fleet owned by the firm 1992-1997
Adoption of computerized dispatching (TECH)	Firm	Explanatory variable measuring productivity-enhancing information technology adoption	Binary variable equal to one if the firm adopted computerized dispatching between 1992 and 1997, and zero otherwise
Control variables			
Δlog taxicab capital	Firm	Change in firm size control	Change in the logged value of firm taxicab capital 1992-1997
Δlog taxicab capital^2	Firm	Change in firm size control (non-linear effects)	Change in the logged value of firm taxicab capital squared 1992-1997
ΔFleet-owned taxicabs market$_{-i}$	Market	Change in market-level vertical integration control	Percentage change in the proportion of fleet owned taxicabs in other fleets in the same market
Δlog(taxis in the market$_{-i}$)	Market	Market growth control in the focal product (taxicabs)	Change in the log number of taxicabs in other firms in the same market 1992-1997
Δlog(limousines in the market$_{-i}$)	Market	Market growth control in substitute products (limousines)	Change in the log number of limousines in other firms in the same market 1992-1997
Δlog limousine capital	Firm	Change in firm scope control	Change in the logged value of firm limousine capital 1992-1997
Δlog limousine capital^2	Firm	Change in firm scope control (non-linear effects)	Change in the logged value of firm limousine capital 1992-1997
Δlog county population	Market	Control for changes in market demand	Change in log market population 1992-1997
Instruments			
Avg. taxicabs/fleet in the market $_{-i}$	Market	Instrument for TECH	The number of taxicabs per fleet (excluding the focal firm) in the same market in 1992
Log market population	Market	Instrument for TECH, numerator of population density	The log of market populations in 1992
Log market size (miles^2)	Market	Instrument for TECH, denominator of population density	The log of market land area in 1992

Table 2 Descriptive Statistics

n=244	1992		1997	
	Mean	Std dev	Mean	Std dev
Adoption of computerized dispatching	0.02	0.17	0.36	0.48
Fleet-owned taxicabs (share)	0.89	0.30	0.66	0.39
Total taxicabs	52	112	67	131
Fleet-owned taxicabs	46	110	45	112
Driver-owned taxicabs	6	29	22	72
Taxicab capital ($000)	546	1,321	864	1,887
Total limousines	0	0	7	17
Limousine capital ($000)	7	52	74	189
Taxicab revenue (000)	1,283	2,808	1,640	3,954
Corporation	0.84	0.38	0.84	0.39
Market fleet-owned taxicabs$_{-i}$ (share)	0.63	0.33	0.36	0.23
Taxicabs in the market	171	391	328	508
Limousines in the market	44	112	113	242
County population (000)	730	1,079	814	1,170
County square miles	1,018	1,455	1,038	1,594
All firms	Total 1992		Total 1997	
Taxicab revenue ($M)	521		669	
Number of taxicabs	20,014		29,960	
Number of fleet-owned taxicabs	16,426		18,303	
Number of fleets	1,020		1,106	

The n=244 sample includes firms that responded to at least one of the taxicab technology surveys (TCRP or author), could be matched to the Economic Census and meets all of the following sampling criteria: SIC code 4121 (taxicabs) in 1992, taxicab revenue ≥ $10K, and at least 2 taxicabs in both 1992 and 1997.
"All firms" includes firms that meet the sampling criteria in at least one year (1992 or 1997).
Note that Census Bureau restrictions prohibit publication of minimum and maximum variable values.

Table 3 Size distribution of firms and computerized dispatching technology adoption

1992 fleet size	Number of firms by 1992 size category (count)	Average size by firm by 1992 size category (taxicabs per firm)	Percentage of firms adopting TECH 1992-1997
2 taxicabs	8	2	0%
3-4 taxicabs	32	4	19%
5-9 taxicabs	48	8	15%
10-24 taxicabs	59	16	25%
25-49 taxicabs	40	36	38%
≥ 50 taxicabs	57	164	70%
Total	244	52	34%

The sample includes firms that responded to at least one of the taxicab technology surveys (TCRP or author), could be matched to the Economic Census and meets all of the following sampling criteria: SIC code 4121 (taxicabs) in 1992, taxicab revenue ≥ $10K, and at least 2 taxicabs in both 1992 and 1997.

Table 4 Adoption of computerized dispatching technology and asset ownership: no controls

Dep. variable = Change in the % of vehicles in the fleet owned by the firm (ΔFOWN)						
	(1) OLS		(2) Matched		(3) 2SLS	
Adoption of computerized dispatching (TECH)	0.13	**	0.13	**	0.48	**
	(0.06)		(0.06)		(0.19)	
Constant	-0.29	***	-0.41	***	-0.40	***
	(0.04)		(0.05)		(0.07)	
R^2 / Psuedo-R^2	0.03		0.02		n/a	
N	244		223		244	
2SLS 1st stage summary statistics						
F-statistic					8.2	
t-statistic on avg. taxicabs/fleet in the market $_{-i}$					4.1	
t-statistic on log market population					2.2	
t-statistic on log market size (miles^2)					-1.0	
Adjusted R^2					0.08	

Standard errors are robust and clustered at the market (county) level.

The sample includes firms that responded to at least one of the taxicab technology surveys (TCRP or author), could be matched to the Economic Census and meets all of the following sampling criteria: SIC code 4121 (taxicabs) in 1992, taxicab revenue ≥ $10K, and at least 2 taxicabs in both 1992 and 1997.

*** Significant at the 1% level, ** Significant at the 5% level, * Significant at the 10% level

Table 5 Adoption of computerized dispatching technology and asset ownership: controls

Dep. variable = Change in the % of vehicles in the fleet owned by the firm (ΔFOWN)						
	(1) OLS		(2) Matched		(3) 2SLS	
Adoption of computerized dispatching (TECH)	0.12	**	0.13	**	0.45	**
	(0.06)		(0.06)		(0.22)	
Δlog taxicab capital	0.05		0.04		0.06	
	(0.05)		(0.05)		(0.05)	
Δlog taxicab capital^2	-0.01	*	-0.01		-0.02	*
	(0.01)		(0.01)		(0.01)	
ΔFleet-owned taxicabs market$_{-i}$ (%)	0.04		-0.04		-0.00	
	(0.07)		(0.08)		(0.08)	
Δlog(taxicabs in the market$_{-i}$)	0.01		0.01		0.02	
	(0.02)		(0.02)		(0.02)	
Δlog(limousines in the market$_{-i}$)	0.02		0.03		0.03	
	(0.02)		(0.02)		(0.03)	
Δlog limousine capital	-0.04	**	-0.04	**	-0.02	
	(0.02)		(0.02)		(0.02)	
Δlog limousine capital^2	-0.01	*	-0.01	*	-0.01	**
	(0.00)		(0.00)		(0.00)	
Δlog county population	0.02	**	0.02	**	0.03	***
	(0.01)		(0.01)		(0.01)	
Constant	-0.14	***	-0.15	***	-0.27	***
	(0.05)		0.05		(0.10)	
R^2 /Psuedo-R^2	0.20		0.20		n/a	
N	244		223		244	
<u>2SLS 1st stage summary statistics</u>						
F-statistic					4.0	
t-statistic on avg. taxicabs/fleet in the market $_{-i}$					3.5	
t-statistic on log market population					2.4	
t-statistic on log market size (miles^2)					-1.5	
Adjusted R^2					0.12	

Standard errors are robust and clustered at the market (county) level.

The sample includes firms that responded to at least one of the taxicab technology surveys (TCRP or author), could be matched to the Economic Census and meets all of the following sampling criteria: SIC code 4121 (taxicabs) in 1992, taxicab revenue ≥ $10K, and at least 2 taxicabs in both 1992 and 1997.

*** Significant at the 1% level, ** Significant at the 5% level, * Significant at the 10% level

Technical appendix

Proof of Lemma 1

Suppose $x < p+b$, so there is no contracting between skilled asset-owners and the fleet. Skilled workers will prefer rental to owning as long as $\theta - b < \theta + (1-\theta)\beta - x$, which implies that the firm's supply of assets is $\theta^* = (\beta+b-x)/\beta$. Now consider the firm's second-period choice of p. Skilled asset owners will contract with the fleet if and only if $\theta < \theta+(1-\theta)\beta-p$, so the firm's demand curve is $D(p)=1-\theta^*-p/\beta$. Substituting θ^* and solving for the optimal p reveals that p* = (x-b)/2, which contradicts our assumption that $x < p+b$.

Solving for equilibrium prices and quantities

When $\theta^U > \theta^L$ the firm's objective is $\Pi(p,b) = [\theta^U - \theta^L]\, p + \theta^L\, [\beta - b]$. Substituting $\theta^U = (\beta - p)/\beta$ and $\theta^L = (b+p+w-\beta)/(1-\beta)$, into $\Pi(p,b)$ and taking derivatives with respect to p and b yields the necessary first-order conditions (which are also sufficient conditions, since $\Pi(p,b)$ is quadratic in both p and b):

FOC (b): $2(\beta - b - p) - w = 0$
FOC (p): $1 + (2\beta - 2b - w)/(1-\beta) - 2p/\beta\,(1-\beta) = 0$

Plugging FOC (b) into FOC (p), and solving for p yields $p^*=\beta/2$, and plugging that solution back into FOC (b) yields $b^* = (\beta-w)/2$. Finally, replacing p^* and b^* in the expressions for θ^U and θ^L yields $\theta^U = ½$ and $\theta^L = w/2(1-\beta)$. Thus, $\theta^U > \theta^L$ if and only if $w<(1-\beta)$. When $w>(1-\beta)$, there is no contracting, so $\Pi(p,b) = (b+w)[\beta-b]$, and the firm's optimal offer price is $b^* = (\beta + w)/2$.