Industry Shakeouts and Technological Change

Steven Klepper, Carnegie Mellon University
Kenneth L. Simons, Royal Holloway, University of London

1999
Date of this version: May 1999
Print date: 4 May, 1999

Steven Klepper
Dept. of Social & Decision Sciences
Carnegie Mellon University
Pittsburgh, PA 15213
USA

phone +1 412 269 3235
fax +1 412 268 6938
email sk3f@andrew.cmu.edu

Kenneth L. Simons
Dept. of Economics
Royal Holloway College
University of London
Egham, Surrey TW20 0EX
UK
phone +44 1784 443909
fax +44 1784 439534
email K.Simons@rhbnc.ac.uk

Industry Shakeouts and Technological Change

Steven Klepper, Carnegie Mellon University
Kenneth L. Simons, Royal Holloway, University of London

Abstract

We analyze new products that experience an initial rise and then extreme shakeout in their number of manufacturers, probing the causes of industry shakeouts and the resulting market concentration. Novel data are collected on producer survival and innovation for automobiles, tires, televisions, and penicillin. Hazard analyses indicate that earlier entrants had persistently lower hazards during the shakeouts, which is related to their greater rates of innovation. Our findings suggest shakeouts are not triggered by particular technological or other events but are part of a competitive process in which the most able early entrants achieve dominant market positions through innovation. (JEL L1, L13, O31)

Industry Shakeouts and Technological Change

Steven Klepper, Carnegie Mellon University
Kenneth L. Simons, Royal Holloway, University of London

After a buildup in the number of firms, new industries commonly experience a shakeout in which the number of firms falls sharply. Among a sample of 46 major new products analyzed by Gort and Klepper (1982) and Klepper and Graddy (1980), most products that had evolved for several decades experienced some degree of shakeout, and in extreme cases the number of producers fell by 90% or more over 15 to 20 years despite robust growth in output. Perhaps not surprisingly, severe shakeouts seem to be associated with eventual tight market concentration. Thus, healthy new markets are suddenly characterized by a sharp and sometimes prolonged decline in the number of producers and end up as oligopolies. What could be driving such profound shifts in market structure?

Theories of shakeouts tend to fall into two camps. In one view, a particular development or event triggers rapid changes in the competitive process. A wave of exit and a sharp decrease in entry result, driving down the number of firms. In a second view, forces of competition operate relentlessly, propelling a few strong firms to market dominance while the weak majority of firms perish. Entry eventually becomes untenable, and continued exit steadily drives the number of firms downward. A number of theories of both types implicate technological change as a key component of the process leading to shakeouts.

Discriminating tests of particular theories have been limited, largely because of the absence of the requisite data needed for such tests, and even fewer attempts have been made to test theories against each other. Thus, our understanding is limited concerning which theories, or which aspects of the theories, help explain the dynamic processes at work in shakeouts. Yet it is important to better understand shakeouts, for two reasons. First, the determinants of market concentration may be better understood by considering the dynamic processes through which concentration arises. Moreover, the number of firms is itself a market structure characteristic worthy of understanding, as it has been associated with diversity of new ideas that can bring about changes in a market. Second, shakeouts often occur in industries subject to high rates of technological change and thus provide an unusual opportunity to analyze the relationship between technology and market structure as it plays out over time. This relationship is the subject of much recent work that attempts to understand technology and market structure as either coevolving (e.g., Nelson and Winter, 1978; Flaherty, 1980; Metcalfe and Gibbons, 1988) or simultaneously determined (e.g., Dasgupta and Stiglitz, 1980; Shaked and Sutton, 1987; Sutton, 1998).

The main purpose of this paper is to analyze empirically the determinants of shakeouts in four major new products that experienced severe shakeouts: automobiles, tires, televisions, and penicillin. The products span a wide range of technologies and differ greatly in the availability of substitutes, suggesting that any common patterns among them are likely to apply as well to other products experiencing shakeouts. Theories of shakeouts featuring technological change serve as a lens to focus our empirical analysis. Guided by the theories, we examine patterns of firm survival, especially the relationship between firm exit rates and time of entry and the timing of the shakeout. We also consider the role of innovation in conditioning firm survival.

To carry out our analysis, for each product we catalog nearly every producer over many decades and identify their years of entry and exit using annual editions of industrial trade registers. We used additional information from many sources to track name, address, and ownership changes, including mergers and acquisitions, to remove biases that often afflict firm survival data. In a second stage we went further, collecting information about each firm's product and process innovations. Where possible we tapped lists of innovations developed by others, which we supplemented with information culled from extensive review of relevant technical journals. The data provide unique detail with which to assess the determinants of entry, exit, and shakeouts and their relation to technological change.

We analyze exit patterns for each product in considerable detail. The patterns do not reveal marked increases in exit rates around the start of the shakeout that would be indicative of shakeouts being triggered by particular events. Rather, by the time of the shakeout early entrants had much lower exit rates that persisted over time, suggesting that shakeouts are part of a competitive process that propels some of the earliest entrants to solidifying market dominance. Technological advance played a key role in this process for each product. Despite the crudeness of our data on innovation and technology adoption, they clearly show that innovation was dominated by early entrants. Furthermore, innovation was the driving force behind the longer survival of the early entrants and was a key factor influencing the survival of entrants from all periods. These findings concur with our earlier detailed qualitative analysis of technological change in the four products (Klepper and Simons, 1997), which indicated that firms continually had to maintain extensive R&D and engineering efforts in order to keep pace with large numbers of competitively crucial product and process improvements.

The phenomena of early-entrant advantages and rich-get-richer dynamics in competition between firms have often been demonstrated in past research. The novelty of our findings is that we show these dynamics consistently occurred in four major new products that experienced severe shakeouts. That a sustained early-entrant advantage should occur for industries with shakeouts has not been at all obvious. Moreover, the role of technological change in the process of shakeouts has also not been clear, and we clarify its importance in our four shakeout products.

The paper is organized as follows. Section I describes the two main theoretical perspectives on how technological change contributes to shakeouts. It draws out contrasting predictions of the theories that are used to structure the empirical analysis. Section II describes the firm survival data that were collected. An overview of entry, exit, and the shakeout is provided in each of the products, and the role of output growth and international trade in each of the shakeouts is reviewed. Section III presents analyses of the effect of entry time and the timing of the shakeout on firm exit rates. Section IV analyzes the extent to which innovation contributed to the advantages of early entrants and more generally conditioned the survival of all firms. Section V contains concluding remarks.

I. Contrasting Perspectives on Industry Shakeouts

Theories about the evolution of industries subject to shakeouts can be classified into two groups. One, which we call event theories, conjecture a well defined event or development that precipitates the shakeout. The event alters the basis of competition. It increases the value of experience, which makes entry more difficult and consequently causes entry to decline. It increases exit by forcing out of the industry firms less able to adapt to the new basis of competition. With exit rising and entry declining, a shakeout occurs. The second group of theories, which we call competitive advantage theories, posit persistent firm heterogeneity coupled with intensifying competition over time. The intensification of competition eventually causes entry to become unprofitable but exit continues as the least able firms are forced out of the industry, giving rise to a shakeout.

We focus on variants of each theory that feature technological change. These theories are not only representative of their broader categories, but they tend to involve formal models which make it possible to derive distinctive testable implications. They also enable us to probe the relationship between technological change and market structure and the forces affecting the rate and nature of technological change, both important topics in their own right.

Events Triggering Shakeouts

In the event theories we consider, shakeouts are triggered by specific technological events. Initially firms enter and populate a new product industry, reaching either a steady state number of producers (Jovanovic and MacDonald, 1994) or a regime in which entry and exit continue and firms break into the market partly by innovating new product variants (Utterback and Suárez, 1993). At some time, an event occurs that changes the nature of the steady state or the competitive regime.

The technological event drives the industry's dynamics. In Jovanovic and MacDonald's theory, which we label the **radical invention theory**, a major invention occurs from outside the industry, and firms can use the invention to enhance their products or manufacturing techniques. A surge of entry may occur as firms seek to exploit the profit opportunity triggered by the invention, and all entry occurs immediately to reap the greatest expected returns (which equal the normal rate of return given free entry) from the invention. Both incumbents and new entrants race to adapt their products and processes to take advantage of the invention. Firms that succeed at the technology adoption gain lower unit costs and expand to a greater optimal size, while firms that fail to adapt quickly enough become unprofitable and exit. With all entry occurring immediately, the subsequent exit of firms contributes to a shakeout.

In Utterback and Suárez's theory, which we label the **dominant design theory**, a *de facto* dominant design emerges that sets standards for the product. Consumer demand shifts toward the standardized design, and firms compete to produce the standard product at the lowest possible cost. Entry slows as opportunities to break into the market on the basis of new product designs are diminished. Exit rises as firms shift from a past regime of product innovation to a new regime of process improvement and firms that do not succeed at process innovation are driven out of business. The combination of a fall in entry and a rise in exit yields the shakeout.

Both theories link survival during the shakeout to adaptation to the new technological environment. Data are rarely available to test whether survivors during the shakeout were in fact firms that better adapted to the new technological regime. Fortunately, the theories have other distinctive implications regarding firm survival that can be tested. This is especially true of the radical invention theory, which is formally modeled in Jovanovic and MacDonald (1994). The dominant design theory, as explicated in Utterback and Suárez (1993), Suárez and Utterback (1995), and Christensen, Suárez and Utterback (1998), is less precise but suggests similar firm survival dynamics to Jovanovic and MacDonald.

In Jovanovic and MacDonald's model, firms initially enter a new industry until expected profits are driven to zero. Subsequently a major invention occurs which opens up new possibilities for innovation. Among firms that have mastered the prior technology, in each period firms that have not yet innovated based on the new technology have a constant probability of doing so. Over time successful innovators expand, and the pressure of output growth on prices pushes out some fraction of the unsuccessful innovators. Hence the hazard of exit rises temporarily until the last unsuccessful innovators exit. Incumbents have an advantage over firms that enter after the major invention stemming from greater technology-related experience, embodied as a one-period head start at innovation. Given their head start, in every period a greater fraction of the pre-invention entrants have innovated than the post-invention entrants and hence they have lower rates of exit. In the variant of Jovanovic and MacDonald's model in which the shakeout is dispersed over time, the rate of exit of both early and late entrants must decline over time since the percentage of firms that have not yet innovated declines and the probability of innovation is the same in every period.[1] Eventually all unsuccessful innovators exit, and the exit rate of both types of firms converges to zero or to the pre-invention exit rate, all else equal. The model is silent regarding other factors such as firm age that might play a role in the exit process.

The dominant design theory is not based on a formal model and thus its firm survival implications are less well motivated. A key feature of the theory is that the emergence of the dominant design changes the basis for competition, which is difficult for some firms to adapt to,

---

[1] Denote the fraction of non-innovators among surviving firms, surviving early entrants, and surviving late entrants as x_t, y_t, and z_t respectively, for t greater than or equal to the first period in which firms exit following the major invention. As Jovanovic and MacDonald show, x_t must decline over time, and it is easy to show that the same property holds for y_t and z_t. As Jovanovic and MacDonald indicate, the price p remains constant once the first exit has occurred following the major invention, and therefore industry output must remain constant. The fraction of non-innovators that innovate in period t is r. Hence in period t the fraction of all firms that innovate is rx_t, and the similar fractions for early and late entrants are ry_t and rz_t. Since all innovators expand from output q^l to q^h, for each innovator there must be $(q^h - q^l)/q^l$ exits among non-innovators so that output remains constant. Hence the fraction of all firms, early entrants, and late entrants that have survived but exit in period t are kx_t, ky_t, and kz_t respectively, where $k = r(q^h - q^l)/q^l$. Since k is a constant and x_t, y_t, and z_t decline over time, the rate of exit must fall over time among all firms and within each cohort of entrants. Jovanovic and MacDonald make no assumption about the composition of firms that exit, and we presume, consistent with the intuition of their model, that within each period non-innovators have equal rates of exit regardless of entry time.

causing them to exit. Although the impetus for exit is different than in Jovanovic and MacDonald, a similar process of adaptation to the changed environment might be envisioned. The exit rate of firms would be expected to be high initially as firms struggle to adapt to the new environment. As some firms succeed at adapting and others exit, the percentage of firms at risk of exiting due to unsuccessful adaptation will fall, causing the exit rate to decline over time toward some new (equilibrium) rate. Utterback and Suárez (1993) and Suárez and Utterback (1995) conjecture that experience will make it easier for firms to adapt to the new environment, so that at the start of the shakeout earlier entrants should have a lower hazard rate, similar to Jovanovic and MacDonald. Alternatively, Christensen, Suárez and Utterback (1998) conjecture that in fast changing environments, it may be easier for firms that have entered shortly before the emergence of the dominant design to adapt to the new environment because they are less committed to technologies rendered obsolete by the dominant design. In either case, with unsuccessful adapters of all vintages exiting over time, it might be expected that any differences in cohort exit rates would decline over the course of the shakeout, as implied by Jovanovic and MacDonald's model.

Emerging Competitive Advantage Yielding Shakeouts

In the competitive advantage theories, shakeouts emerge from a continual process of competition rather than being triggered by particular technological or other events. These theories assume that entrants are heterogeneous and over time the degree of competition in a new industry intensifies as new firms enter and the most able firms expand. Eventually entry becomes unprofitable and entry ceases, but exit continues as the least able firms are driven from the market, contributing to a shakeout.

There are a number of theories of this type that involve different mechanisms, including theories from organizational ecology that do not feature technology (Carroll and Hannan, 1989). We focus on a theory developed in Klepper (1999), which features the role of technological change in contributing to shakeouts. The theory is similar to an earlier model by Klepper (1996), but explicitly derives implications for firm exit rates that can be usefully compared to the event theories.

The theory features a process of dynamic increasing returns to R&D in which firm size is limited by convex costs of growth, and larger firms benefit most from R&D – and hence choose to perform the most R&D – because they apply the resulting unit cost reductions and quality improvements to the largest amounts of output. Firms also differ in terms of the productivity of their R&D based on prior experience producing related products or for startups the experience of their founders. Over time new entrants arise with the requisite R&D capabilities to enter the industry. As entry and growth occur over time, industry output expands, causing the price per unit of quality to fall. Entrants consequently must be increasingly able at R&D in order to be profitable, and hence the minimum R&D productivity required for entry rises until eventually even the most capable potential entrants cannot profitably enter. The earliest entrants with the greatest R&D productivity grow to be largest and hence perform the most R&D, which provides them with a competitive advantage. Even after entry ceases, they continue to expand, forcing out of the market the less able firms and later entrants. This causes an inexorable decline in the number of producers.

The theory yields distinctive implications regarding the hazard of exit. At the start of the new industry, entry is easiest and the greatest range of firms enters in terms of their R&D capability. The less capable firms have a higher hazard in every period, so over time they disproportionately exit, causing the hazard rate of the earliest entrants to decline. Later entry cohorts have less diversity due to the greater difficulty of entry and thus the hazard declines less with age. The decline in the hazard with age is less in industries in which early entrants are less diverse, which are industries in which a high percentage of early entrants are experienced and thus have similar R&D capabilities. The other determinant of the hazard is the time of entry. Given the costs of growth, all else equal in every period earlier entering firms are larger and hence reap the greatest returns from R&D, making them more profitable and hence less prone to exit. At young ages, the presence of a greater percentage of firms with lower R&D productivity among the early entrants might offset this entry time advantage. But by the time firms reach older ages and the less capable early entrants have been selected from the market, earlier entrants must have a lower hazard than later entrants at a comparable age. In turn, when the industry has evolved for some time and the earlier entrants have reached older ages, they also must have a lower hazard than later entrants (of younger age).

Contrasting Implications of the Theories

The different theoretical perspectives yield distinctive implications about firm hazard rates on three dimensions: 1) how the hazard of incumbent firms changes at the outset of the shakeout and the nature of the evolution of the hazard of both incumbents and shakeout entrants as the shakeout proceeds; 2) differences during the shakeout in the hazards of firms that entered at different times; 3) the effect of age on the hazard. Each dimension is reviewed in turn.

Consider first changes in the hazard of incumbent firms at the outset of the shakeout. In the event theories, the technological development triggering the shakeout alters the basis of competition and initially raises the hazard of incumbent firms, so that the hazard of firms that entered prior to the shakeout rises around the start of the shakeout. The triggering development is also expected to raise the value of experience. Therefore, firms entering after the start of the shakeout should initially have a higher hazard than preshakeout entrants. As the shakeout proceeds, firms that adapt to the new environment remain in the industry and those that do not adapt exit, causing the fraction of firms in each cohort of entrants that have not yet adapted to the event to decline over time. This implies a decline in the hazard of all cohorts of entrants as the shakeout proceeds, with eventually the hazard returning to its preshakeout level, all else equal. In contrast, in the competitive advantage theory, no increase in the hazard is implied at the time of the shakeout. Apart from effects of age on the hazard, there is also no reason for the hazard to decline as the shakeout proceeds.

Consider next differences across entry cohorts in their hazard during the shakeout. The event theories imply that inter-cohort differences in the hazard emerge when the shakeout begins. In the radical invention theory and in the original version of the dominant design theory (Suárez and Utterback, 1995), the hazard is lower the earlier the time of entry. But in the later articulation of the dominant design theory for fast changing environments, the hazard is lowest for firms that enter in a brief window just before the shakeout, which was operationalized as four years prior to the shakeout (Christensen, Suárez, and Utterback, 1998). Differences in cohort hazard rates should dissipate over time, though, as the fraction of firms that have not successfully adapted to the new environment declines. The competitive advantage theory also predicts that by the time of the shakeout, the hazard should be lower the earlier the time of entry. But in contrast to the event theories, the competitive advantage theory predicts that entry cohort differences in hazard rates will not dissipate over time and might even grow.

Last, only the competitive advantage theory has implications regarding the effect of age on the hazard. It predicts the hazard will decline with age, particularly in industries in which there is a lot of diversity among the early entrants. Such diversity is expected to be greater for industries in which a small percentage of entrants have experience producing related products prior to entry.

The different firm survival implications of the theories are used to probe the determinants of shakeouts. We also exploit data on innovation to explore the relationship between firm survival and innovation. Here the theories overlap considerably. They all predict that during the shakeout the hazard of exit should be lower for firms that are better innovators. They all also predict that earlier entrants should be better innovators during the shakeout. The competitive advantage theory also predicts these patterns will hold in all eras, not just the shakeout, and it stresses the importance of all innovations whereas the event theories stress the importance of innovations brought about by the event triggering the shakeout. While the distinctions regarding innovation between the theories will be difficult to test given the data we were able to collect on innovation, the predictions provide a way of checking on the internal consistency of the theories, which all portray innovation as the key force conditioning survival during the shakeout. As such, the predictions also provide a way of testing the theories against others, such as those developed by organizational ecologists, that do not see technological change as a key force driving entry, exit, and the evolution of a concentrated market structure in new industries.

II. The Shakeouts

To probe the determinants of shakeouts, we use a sample of four industries that experienced severe shakeouts: automobiles, tires, televisions, and penicillin. A major factor influencing our choice of products was the availability of data. Among the products, one (tires) has also been considered by Jovanovic and MacDonald and two (automobiles and TVs) by Utterback and Suárez in applying their theories to particular industries.

This section provides key background information about the nature of the data and our treatment of firm entry and exit. Additional information on data sources and methods appears in an Appendix. Patterns in the number of firms, entry, and exit in each product are reviewed along with background information about market concentration, industry output, and the limited effects of international competition on the shakeouts in each of the products.

Data Types, Sources, and Treatment

To collect firm entry and exit data, we identified lists and annual directories of the manufacturers of each product. Each source we consulted attempted to catalog all U.S. producers of the product, and we compared alternative sources to investigate their reliability. We chose the source or (for penicillin) combination of sources for each product that best included all manufacturers while excluding firms that never produced. The sources used appear to reliably date the production start and end dates for most firms, to exclude almost all non-producers, and to include the vast majority of producers. Firm lists in annual trade registers were combined by cataloging all producers that appeared in every edition of each register and the years in which each firm was listed.

Changing firm names pose a problem with most firm survival data. Name changes create the impression that an incumbent firm exited and a new firm entered, when in fact a single firm continued to produce. Biased empirical patterns may result. Notably, if early entrants have a low hazard of exit at old ages, some apparent later entrants will actually be early entrants with new names and an artificially low hazard, biasing the observed hazard upward for early entrants and downward for later entrants. To prevent such biases, we recorded annually each firm's name and street address. We combined the histories of firms with identical street addresses in nearby years, treated firms as continuing producers despite minor name changes, and verified firm histories using available literature. Also, if a register listed multiple branches of a firm in one year, we considered the separate branches as belonging to a single producer. Thus illusionary entry and exit and duplication of firms are removed from the data.

Mergers and acquisitions were recorded using systematic records that had been compiled by industry experts. When merger and acquisition occurred, the largest of the merged entities was treated as the continuing producer, and other entities were recorded as exiting. The output of the product being analyzed alone was considered in assessing firm size, and if output could not be estimated then the firm whose name was retained after the merger was coded as the continuing producer. Acquisitions by firms that did not already produce the product were ignored, as they simply implied continued production with new ownership. Most firms in these products were quite small and hence acquisitions represent only 6% of the exit recorded in the four products. Nonetheless, acquisitions clearly differ from cessation of production, in that acquired firms might have continued production if they were not acquired. Hence in the empirical analyses of Sections 3-4, we treat acquired firms as censored at the time of merger, as if no further data were available regarding their continued production.[2]

Sample Properties

Annual counts of the number of firms, entry, and exit in each of the four products appear in Figure 1. The number of producers in each product rose dramatically during a period of one to three decades following the inception of commercial production. After attaining its peak, the number of U.S.-owned producers fell for each product for more than three decades. In automobiles, tires, televisions, and penicillin, shakeouts began after the number of firms peaked in 1909, 1922, 1951, and 1952 respectively. From peak to eventual low, the number of producers in each product was reduced by 97%, 92%, 88% (100% of U.S.-owned producers), and 70% respectively.

Entry was concentrated before the shakeout in each product. In automobiles and tires, entry rose over time initially following the inception of the industry, while in televisions and penicillin the greatest annual numbers of entrants occurred shortly after or during World War II. Entry decreased dramatically once the shakeout began, in accord with all the theories. In automobiles, entry dropped by about two thirds when the shakeout began in 1909, then fell to near zero by the early 1920s. In the other three products, entry fell to near zero by a few years after the shakeout began.

Exits, not surprisingly, were most when the greatest number of firms were available to exit. Merger-related exits are included in the exit data of Figure 1, and constitute 4%, 1%, 6%,

---

[2] Often acquired firms appear to have been foundering, suggesting that they might have exited if they had not been acquired. Accordingly, we also analyzed the data treating mergers as exits, with similar results.

and 0% of exits before and 7%, 5%, 11%, and 3% of exits after the beginning of each respective shakeout. Exit continued even in the later years of each product, driving the number of firms down since total exit exceeded entry. The hazard of exit and its determinants will be probed in upcoming sections of the paper.

Tight oligopolies arose in the four industries. In automobiles, the top two firms went from 38% of unit sales in 1911 to over 60% by the 1920s, and the top three firms held a share of over 80% in the 1930s. In tires, the big four firms went from 53% of unit sales in 1926 to 72% in 1933. In televisions, five major firms held at least 67% of unit sales in 1958, and by 1968 two firms alone sold 50% of color sets before losing the market to foreign competitors. In penicillin, four large producers held 60% of dollar sales in 1960 and 69% in 1973. Thus to the extent evidence is available concentration increased during the middle years of each shakeout, and more importantly all four markets became highly concentrated.[3]

Industry output grew dramatically even after each of the shakeouts began. Automobile output grew from 127,000 cars in 1909 to 1.7 million in 1919 and 5.3 million in 1929, and would rise further after setbacks during the Depression and World War II. Tire output grew from 40 million tires in 1922 to 73 million in 1928, and as in automobiles output would grow further following World War II. Television output leveled off after attaining a peak of over 7 million sets in 1950, but then rose to over 11 million sets with the growth of color television set production in the 1960s and 1970s. Penicillin output grew from 671,000 pounds in 1952 to 10,200,000 pounds in 1987.[4]

---

[3] Market share data cited were obtained from FTC (1939, p. 20), French (1991, p. 47), Levy (1981, pp. 84-88), and Schwartzman (1976, pp. 131-132).

[4] Industry output data cited were obtained from FTC (1939, p. 7), Gaffey (1940, p. 54), Levy (1981, pp. 99-100, 112), and US Tariff Commission (1952-1987).

Competition from abroad was quite limited during the shakeouts of each product and thus could not be responsible for the shakeouts. In each product except televisions, there were few imports and little foreign direct investment during the period studied. Only in televisions was there much impact of foreign competition, but imports and foreign direct investment in televisions did not become substantial until around 1970.

III. Firm Exit, the Shakeout, and Entry Time

In this section, the firm survival implications of the theories are tested. An econometric model of the hazard of exit is specified and estimated for each product using the firm data on the year of entry and exit. The data are also analyzed graphically and supplemented by market share data for the largest firms.

Specification of the Econometric Model

The event and competitive advantage theories are not nested, so no single model can faithfully represent all aspects of the two theories. But it is possible to specify a model that accommodates all of the distinctive firm survival implications of each theory. Based on the discussion in the prior section, the model needs to have the following features. It must distinguish between entrants before and during the shakeout to test for a differential response of each group to the shakeout. Among the entrants prior to the shakeout, it must distinguish between earlier and later entrants to test whether the later preshakeout entrants fared better during the shakeout, as predicted by the recent variant of the dominant design theory. It must allow the hazard of each cohort of entrants to rise and be greater at the start of the shakeout, as predicted by the event theories. It must also allow the hazard of each cohort of entrants to change at a different rate as the shakeout proceeds to test for a general decline and convergence predicted by the event theories versus a persistent and possibly widening difference predicted by the competitive advantage theory. Last, it must allow firm age to affect the hazard to accommodate the effects of heterogeneity cum selection emphasized by the competitive advantage theory and other factors associated with age such as experience that may also affect the hazard.

The following model, which possesses these features, is used to test the theories:

(1) $$r_{it} = h(age_{it}) \exp\{\beta_1 S_t + \beta_2 cohort\ 2_i S_t + \beta_3 cohort\ 3_i S_t + \beta_4 S_t(t - S) + \beta_5 cohort\ 2_i S_t\ (t - S) + \beta_6 cohort\ 3_i S_t\ (t - S)\}.$$

The dependent variable r_{it} is the hazard of firm i in year t, age_{it} is the age (time since entry) of firm i in year t, $h(age_{it})$ is a function calibrating the effect of age on the hazard, S_t is a 1-0 dummy equal to 1 for firm i in the years of the shakeout, S is the year of the peak number of firms (i.e., the start of the shakeout) and t - S is the number of years since the start of the shakeout, and cohort 2_i and cohort 3_i are 1-0 dummies equal to 1 for firms in cohorts 2 and 3 respectively, where cohort 1 is composed of the earliest entrants, cohort 2 the later entrants prior to the shakeout, and cohort 3 the entrants during the shakeout. The first three terms in the exponent allow the hazard of each cohort to differ in the shakeout versus nonshakeout years. For the preshakeout entrants this allows their hazard to rise with the onset of the shakeout and for the shakeout entrants it allows for a higher hazard at the start of the shakeout. The second three terms in the exponent allow the hazard of each cohort to change as the shakeout proceeds, with separate rates of change for each cohort to allow for a possible convergence (or divergence) in the hazards of the preshakeout and shakeout entrants. The function $h(age_{it})$ allows the hazard to vary with age comparably in each cohort.

The model is operationalized as follows. First, the sample of firms is restricted to entrants from the beginning of the industry through year S+10. All the theories predict entry becoming negligible as the shakeout proceeds. While this was satisfied in all four products, given the long histories of each product the total number of entrants after year S+10 is not trivial. It does not seem sensible to treat entrants many years after the start of the shakeout as affected by events that might have triggered the shakeout, and so the sample is restricted to firms entering within ten years of the shakeout.[5] Second, the shakeout is restricted to the 15 years following the peak in the number of producers, so S_t equals one for years S+1, S+2, ..., S+15 and 0 for all earlier and later years. The event-based theories predict the industry eventually attains a new equilibrium some time after the start of the shakeout. This suggests that adjustment to a triggering event should occur within a limited time frame, which we arbitrarily set to 15 years.[6] Third, in autos, tires, and penicillin the preshakeout entrants were divided by putting all entrants in the five years preceding the shakeout into cohort 2 and all earlier entrants into cohort 1. Televisions had only six years of entrants prior to the start of the shakeout, so the first two years of entrants were put in cohort 1 and the next four years of entrants in cohort 2. The definitions of the cohorts and number of firms in each cohort for the four products are presented in Table 1. Last, since we had little guidance on the form of the function $h(age_{it})$, three alternative specifications were employed: the exponential, exp{c}, with parameter c; the Weibull, $p\exp\{c\}age_{it}^{p-1}$, with parameters c and p (or ln p, as it is parameterized below); and the Cox. The

[5] The model was also estimated with all firms, which had little effect on the estimates.
[6] We also estimated the model setting S_t equal to 1 for all years after S, which allows for an indefinite period of adjustment to the shakeout. This had little effect on the estimates.

exponential specifies the hazard as a constant c, independent of age, the Weibull allows for a monotonic change in the hazard, with a decline (rise) corresponding to ln p < (>) 0, and the Cox imposes no structure on the hazard, effectively allowing a different value for the hazard at each (integer) age.[7]

Predictions of the Theories

The predictions of the event theories and the competitive advantage theory are summarized in Table 2. Consider first β_1, β_2, and β_3. The parameter β_1 calibrates the effect of the start of the shakeout on the hazard of cohort 1, and $\beta_1 + \beta_2$ and $\beta_1 + \beta_3$ play the analogous role for cohorts 2 and 3, with β_2 and β_3 representing the additional effects of the shakeout on the hazards of cohorts 2 and 3. The event theories predict a rise/greater value of the hazard at the start of the shakeout for all firms, which implies $\beta_1 > 0$, $\beta_1 + \beta_2 > 0$, and $\beta_1 + \beta_3 > 0$. Both also predict shakeout entrants having a higher initial hazard during the shakeout than preshakeout entrants, which implies $\beta_3 > 0$. The two event theories differ regarding β_2. The recent variant of the dominant design theory predicts the later preshakeout entrants being least affected by the shakeout, implying $\beta_2 < 0$. Alternatively, if experience is advantageous in adjusting to the event

---

[7] Since the three theories are not nested, the model inevitably involves compromises. One is that at each age the hazard of all shakeout entrants is constrained to be the same in each year regardless of when they entered. If the hazard of shakeout entrants declines as the shakeout proceeds, as the event theories predict, this implies that later shakeout entrants suffer a lesser initial (i.e., at age 0) competitive disadvantage than earlier shakeout entrants. This would be consistent with diffusion of information making it easier for later entrants during the shakeout to adapt to the new technology. The opposite, however, was predicted by Suárez and Utterback (1995), although their empirical results provided little support for their conjecture. A second compromise is that before the shakeout and after year S+15, all three cohorts are constrained to have the same hazard. This is not consistent with the competitive advantage theory, but since the entrants in cohort 2 were in the industry for at most five years prior to the shakeout and not many of the entrants in cohorts 2 and 3 survive past year S+15, in practice it may have little effect on the estimates. Last, the model constrains age to have the same effect on the hazard for each cohort. This is also inconsistent with the competitive advantage theory and not addressed by the event theories. While this could be relaxed, the model allows time since the shakeout began to have a different effect on the hazard for each cohort, and it is not feasible to distinguish such effects from cohort specific effects of age on the hazard.

triggering the shakeout, as is assumed in the radical invention theory, then cohort 2 should be more affected by the hazard than cohort 1 but less than cohort 3, which implies $\beta_3 > \beta_2 > 0$. Both of these possibilities are listed in Table 2. In the competitive advantage theory, the shakeout is not triggered by a particular event, so no rise is expected in the hazard of any cohort with the onset of the shakeout. This implies $\beta_1 = 0$. However, by the time of the shakeout, both cohorts of preshakeout entrants have evolved for some time, particularly the first, and the hazards of the three cohorts would be expected to be ordered by the time of entry. This implies $\beta_2 > 0$ and $\beta_3 > 0$, hence $\beta_1 + \beta_2 > 0$ and $\beta_1 + \beta_3 > 0$. Thus, in terms of β_1, β_2, β_3, as Table 2 indicates the main differences in the theories involve whether β_1 is positive (versus 0) and the sign of β_2.

Consider next $\beta_{4,}$ β_5, and β_6. The parameter β_4 calibrates how the hazard of cohort 1 changes as the shakeout proceeds, and $\beta_4 + \beta_5$ and $\beta_4 + \beta_6$ play the analogous role for cohorts 2 and 3, with β_5 and β_6 representing the additional effects of time since the start of the shakeout on the hazards of cohorts 2 and 3. Both event theories predict a fall in the hazard of all cohorts as the shakeout proceeds, which implies $\beta_4 < 0$, $\beta_4 + \beta_5 < 0$, and $\beta_4 + \beta_6 < 0$. Both theories also predict the hazards of the cohorts converging over time. For the radical invention theory, which predicts the hazards of the cohorts ordered by time of entry at the start of the shakeout (i.e., $0 < \beta_2 < \beta_3$), convergence of the hazards of the cohorts implies $\beta_6 < \beta_5 < 0$. In contrast, for the recent version of the dominant design theory, which predicts $\beta_2 < 0 < \beta_3$, convergence implies $\beta_6 < 0 < \beta_5$. Again, both possibilities are listed in Table 2. The competitive advantage theory predicts no effect of the shakeout on cohort hazards and hence no change in cohort hazards as the shakeout proceeds. It also predicts no convergence and even possibly divergence of the hazards of the cohorts over time. Together, this implies $\beta_4 = 0$, and $\beta_5 \geq 0$ and $\beta_6 \geq 0$. Thus, in terms of β_4, β_5, and β_6, as Table 2 indicates the main differences in the theories involve the signs of β_4, β_5, and β_6 and relatedly the signs of $\beta_4 + \beta_5$ and $\beta_4 + \beta_6$.

Last, neither of the event theories predicts how age affects the hazard, but the competitive advantage theory predicts the hazard declines with age due to heterogeneity cum selection. The decline is more severe the greater the heterogeneity among entrants, which for each product is predicted to be greater for the earlier entrants. Among the four products, a majority of the early entrants in televisions produced radios prior to televisions, and nearly all producers of penicillin produced chemicals and/or drugs prior to entry. In contrast, less than 20% of automobile and tire entrants had experience producing related products prior to entry (Klepper, 1999). This suggests that among early entrants there was greater diversity in autos and tires than televisions and penicillin, and hence that the hazard should decline most with age for autos and tires.

Hazard Model Estimates

Maximum-likelihood estimates of the coefficients for the four products are presented in Table 3, first for the exponential hazard, then the Weibull, and last the Cox. The estimates were computed using the program Stata, with mergers and acquisitions treated as censored observations. Standard errors are presented in parentheses.[8]

Consider first the estimates of β_1, β_2, and β_3 for the exponential hazard model. $\hat{\beta}_1$ is positive for tires and penicillin, negative for automobiles and televisions, and significant only for tires. Thus, except for tires, the start of the shakeout does not appear to correspond to a rise in

[8] Standard errors were computed by the robust method with clustering by firm, thus correcting the standard errors for possible within-firm serial correlation in random survival outcomes (Huber, 1967; White, 1982; Lin and Wei, 1989). The differences between robust and unadjusted standard errors averaged only 8.4% of the unadjusted values, suggesting that the model appropriately accounts for serial correlation.

the hazard of the earliest entry cohort, contrary to the predictions of the event theories. All eight values of $\hat{\beta}_2$ and $\hat{\beta}_3$ are positive, and $\hat{\beta}_2$ for automobiles and $\hat{\beta}_2$ and $\hat{\beta}_3$ for tires and televisions are significant (penicillin has the smallest number of observations by far, so its standard errors are larger). Relative to the first cohort, the eight estimates imply magnitudes ranging from a 52% higher hazard in autos for cohort 3 to a 475% higher hazard in televisions for cohort 3. The positive and sizeable values of $\hat{\beta}_3$ for all four products are consistent with all three theories. The positive and sizeable values of $\hat{\beta}_2$ indicate that at the start of the shakeout later preshakeout entrants were at a clear disadvantage relative to the earlier preshakeout entrants, which is consistent with the radical invention and competitive advantage theories but not the recent variant of the dominant design theory. On the other hand, $\hat{\beta}_2$ is greater than $\hat{\beta}_3$ for three of the four products, suggesting that the shakeout entrants had no greater difficulty adjusting initially to the shakeout than the later preshakeout entrants, contrary to the predictions of the radical invention and competitive advantage theories. All eight values of $\hat{\beta}_1 + \hat{\beta}_2$ and $\hat{\beta}_1 + \hat{\beta}_3$ are positive and five are significant, consistent with all three theories. Thus, the estimates indicate that at the start of the shakeout the first cohort of entrants had a considerably lower hazard in all four products than either of the other two cohorts and the hazard of the first cohort did not consistently rise at the start of the shakeout, consistent with the competitive advantage theory. The only departure from the competitive advantage theory is the comparable hazards of the second and third cohorts at the start of the shakeout, but this pattern is also not predicted by the event theories.

Consider next the estimates of β_4, β_5, and β_6 for the exponential model. $\hat{\beta}_4$ is negative for all four products and marginally significant for automobiles and tires. This suggests that the hazard of the first cohort fell as the shakeout proceeded, which is consistent only with the event theories. However, the event theories predict a decline in the hazard after an initial rise in the hazard at the start of the shakeout for the first two cohorts, but the values of $\hat{\beta}_1$ for the four products indicated no such consistent rise for the first cohort. An alternative possibility is that the decline in the hazard of the first cohort reflects the effect of age on the hazard, which is not captured by the exponential model. Regarding $\hat{\beta}_5$ and $\hat{\beta}_6$, six of the eight estimates are positive and one, $\hat{\beta}_6$ for automobiles, is positive and significant. Only for televisions are the estimates negative, where they are sizeable but not statistically significant. Thus the most common pattern involves divergence in the hazards of the later two cohorts relative to the first, which is consistent only with the competitive advantage theory. Furthermore, in all four products $\hat{\beta}_5 < \hat{\beta}_6$, which implies the hazard of the third cohort diverges as well from the second. Thus, while the hazard of the second cohort does not appear to be less than the hazard of the third at the start of the shakeout as reflected in $\hat{\beta}_2$ and $\hat{\beta}_3$, as the shakeout proceeds the predicted pattern appears to emerge. Last, $\hat{\beta}_4 + \hat{\beta}_5$ is negative for all four products and $\hat{\beta}_4 + \hat{\beta}_6$ is negative for two of the four products, with four of the eight estimates negative and significant. These patterns suggest that the hazards of the later preshakeout entrants and to a lesser extent the shakeout entrants also generally decline as the shakeout proceeds, which is consistent only with the event theories. Again, though, the declines may reflect the absence of controls for age on the hazard. Thus, as the shakeout proceeds the hazards of the three cohorts appear to diverge according to their time of entry, which is consistent with the competitive advantage theory. They also appear to decline over time as the shakeout proceeds, which is not predicted by the competitive advantage theory, but this may be due to the absence of controls for age on the hazard.

The estimates for the Weibull and Cox hazards control for the effects of age on the hazard. Consider first the Weibull estimates in the second panel of Table 3. Surprisingly, the estimates do not imply a consistent decrease in the hazard with age. In two of the four products $\ln\hat{p}$ is actually positive, implying that the hazard rises with firm age, and it is significant for automobiles, where $\ln\hat{p} > 0$. This is opposite to the predictions of the competitive advantage theory. Perhaps not surprisingly given the small estimated effects of age, the coefficient estimates are similar to those using the exponential model.

The estimates for the Cox model tell quite a different story. The implied estimates of the hazard for each (integer) age are presented in Table 4 for ages 0-19 and for 10-year age brackets spanning 0-9 to 70-79. The 10-year averages for autos and tires and to a lesser extent televisions suggest a strong decline in the hazard with age, which is in line with the competitive advantage theory but contrasts sharply with the Weibull estimates. The contrast is apparently due to the nonmonotonic decline in the hazard over ages 0-19 in all three products. This seems especially true for autos and tires, where there is a sharp rise in the estimated hazard from age 0 to age 1. Excluding the data points for age 0 and re-estimating the Weibull model for automobiles and tires, $\ln\hat{p}$ becomes –0.11 in automobiles and –0.39 in tires, with the tires estimate significant at the .001 level. This confirms that for these products the Weibull treatment of age is misleading and the Cox treatment more appropriate. The coefficient estimates of the Cox model do not differ greatly from the other two models, although $\hat{\beta}_4$, $\hat{\beta}_4 + \hat{\beta}_5$, and $\hat{\beta}_4 + \hat{\beta}_6$ tend to be modestly larger than in the exponential, suggesting a smaller decline in the cohort hazards as the shakeout proceeds. Thus, the estimates of the Cox model provide modest additional support for the competitive advantage theory.

Hazard Plots

Another perspective on the firm survival patterns can be gained by plotting for each product the annual hazard of the three cohorts of entrants. While the plots sacrifice the ability of the econometric model to separate and test different effects on the hazard, they have the advantage of obviating a number of the more restrictive assumptions of the model, such as age affecting the hazard comparably for all cohorts. As such, they provide complementary evidence to the estimates of the econometric model.

Given the sample sizes of the four products, the annual hazards tend to gyrate greatly, especially in later years, making them difficult to interpret. In order to address this, smoothing techniques are employed. Specifically, for each product the hazard in year t is computed as:

(2) $$h_t = \frac{\sum_{i=-10}^{10} \phi(i) I_{t+i} x_{t+i}}{\sum_{i=-10}^{10} \phi(i) I_{t+i} n_{t+i}},$$

where the weights $\phi(i)$ on years i = 0, 1, 2, ..., 10 away from t equal 1, 0.882, 0.607, 0.325, 0.135, 0.044, 0.011, 2.2×10^{-3}, 3.3×10^{-4}, 4.0×10^{-5}, and 3.7×10^{-6} respectively, I_t is an indicator variable such that if t < S then it equals one for all years less than S and 0 otherwise, and vice versa if t > S, and x_τ and n_τ respectively are the number of exits and firms at risk of exit in year τ. The smoothing of the annual hazard is done with a moving 10-year window around year t with weights that decline away from year t according to a normal distribution with standard deviation of 2. This greatly reduces the annual gyrations in the hazard except for the latest years of the products, for which the sample of survivors becomes quite small. Note that for the 10 years prior to S, the formula for h_t is such that no weight is placed on the hazards of shakeout years, and vice versa for the 10 years after S. This ensures that any abrupt change in the hazard occurring around the start of the shakeout will not be obscured by the smoothing.

The hazard plots for the four products are presented in Figure 2. Consider first the plot for automobiles. Focusing initially on the first cohort of entrants, the long-term trend in the hazard is downward over time, suggesting a long-term decline in the hazard as the firms in the first cohort aged. This is consistent with the estimates of the Cox model. Similar to all three sets of econometric estimates, there is no sign of a rise in the hazard around the start of the shakeout in 1909. Also similar to the econometric estimates, the hazards of cohorts 2 and 3 are roughly twice as great as the hazard of the first cohort around the start of the shakeout. Through the next 25 years or so into the early 1930s, the hazards of both the second and third cohorts moved in tandem with the first, with the hazard of the third cohort greater than the second for most years and the hazard of the second well above the first. The third cohort became extinct in 1940 and only a few firms were left in the second cohort before it became extinct in 1954, making further comparisons difficult. Thus, the patterns in autos conform closely with the competitive advantage theory, with the hazards of the three cohorts ordered by time of entry both at the start of the shakeout and for many years thereafter.

The plot for tires is somewhat different, which again parallels the econometric estimates. Similar to autos, there is a long-term decline in the hazard of the first cohort over time and the first cohort has a markedly lower hazard than the other two from the start of the shakeout through the next 20 years or so to around 1940. This is consistent with the estimates of the Cox model. In contrast to autos, though, there is a noticeable increase in the hazard of the first cohort around the start of the shakeout in 1922 which parallels a sharp rise in the hazard of the second cohort as well. This is consistent with the econometric estimates, which indicated a significant rise in the hazard of both cohorts 1 and 2 at the start of the shakeout. While the patterns are consistent with some kind of event triggering the shakeout, other distinctive factors in the 1920s severely depressed rates of return earned by all tire manufacturers (Reynolds, 1938) and may have caused the hazard rates of all cohorts to rise.[9] A distinctive feature of the plot that was not revealed in the econometric estimates is the convergence of the hazards of all three cohorts after 1940. The plot also indicates very little difference in the hazards of the second and third cohorts. Thus, the patterns for tires conform less to the competitive advantage theory than for autos. They reflect a rise in the hazard at the start of the shakeout not predicted by the competitive advantage theory and an eventual convergence of the hazards of the three cohorts almost 20 years after the start of the shakeout. The latter pattern is not, however, consistent with the event theories, which anticipate a gradual convergence that certainly would be expected to commence a lot earlier than 20 years after the start of the shakeout.

In televisions, the plot reveals a pattern with some features that could not be seen from the econometric estimates. First, there is no clear long-term trend in the hazard for any of the cohorts. This is similar to the Weibull but different from the Cox estimates. Second, and perhaps most interesting, the hazards of the cohorts are ordered by time of entry at the start of the shakeout, then they converge sharply in the first eight years or so of the shakeout through 1960, and then they diverge just as sharply over the next eight to ten years through 1970. After 1970 few firms remain in the later two cohorts, making further comparisons difficult. While the convergence and then divergence of the cohort hazards is not predicted by any of the theories, it may reflect the unusual history of color television, which defined the technological frontier in

[9] A severe price war that occurred throughout the 1920s as well as a recession in 1920-21 and value lost in hedging rubber stocks following an attempt to control world prices have been cited by historians as the reasons for the increased hazard of firms in the 1920s (French, 1991).

televisions throughout the first 20 years of the industry. Color television was unsuccessful and eventually largely withdrawn from the market after being introduced in the 1950s, and was successful only later in the 1960s after subsequent improvements. If the advantage of early entrants is based on innovation, as featured in the competitive advantage theory, then it would be expected that the lower hazard of the earlier entrants would depend critically on the success of color television.

The plot for penicillin reveals little long-term trend in the hazard of any of the cohorts, consistent with the estimates of the Weibull and Cox models, and a persistent difference in cohort hazards by time of entry. Much more so than the econometric estimates, the plot reveals a markedly higher hazard of the third cohort than the second. There is some sign of a rise in the hazard of the first two cohort hazards around the start of the shakeout, as is reflected in the Cox estimates. Otherwise, the patterns conform closely with the competitive advantage theory.

Overall, the plots confirm the impression from the econometric models of a persistent ordering of the cohort hazards by time of entry throughout the shakeouts, as predicted by the competitive advantage theory. While the hazard of the preshakeout entrants appears to rise at the start of the shakeout in tires and possibly penicillin, in neither industry do the hazards of the three entry cohorts converge, as predicted by the event-based theories. It appears that the shakeouts in all four products correspond to a playing out of a competitive process that confers sizeable advantages on earlier entrants.

Market Share Dominance

One last piece of evidence is considered to test the theories. Occasionally sources report the market shares of the leading firms. In Table 5 the U.S. producers are listed that show up in these reports as having at least a 10% share of the market. Their years of entry are also listed.

It is noteworthy that every one of the firms listed was an early entrant. Only one firm that entered in cohorts 2 or 3 in all four products ever attained a 10% market share, and it entered in the very first year of cohort 2 for televisions.[10] Thus, not only did the earlier entrants have markedly lower hazards, but they dominated each of the products. This further establishes the importance of early entry, which is a cornerstone of the competitive advantage theory.

IV. Innovation and Firm Survival

In this section we explore the relationship between innovation and firm survival, focusing especially on the extent to which the lower hazard of the earlier entrants after the start of the shakeouts is related to innovation.

To analyze the influence of innovation on the hazard, we need to develop measures of innovation per firm. This requires reconstructing the technological histories of each product in order to identify the major innovations in the product and the firms that developed them. To

---

[10] Chrysler Corporation in the automobile industry might seem an exception, as it was not incorporated until 1925. In fact, however, Chrysler illustrates the importance of recording actual production and employment entities – as we took care to catalog for all firms in all our products – rather than legal entities or names. The company dates back to the much earlier Maxwell-Briscoe Motor Company, which began manufacturing in 1904. In 1910, it was already selling approximately 20,500 cars, giving it slightly over 10% of the market. Although its sales slipped somewhat over the following years, it built up again to a production of 48,850 cars in 1922, the year before Walter P. Chrysler arrived to take over the company and reorganize it in his name (cf. the entry for Chrysler in Kimes and Clark, Jr. (1996)). While Chrysler's reorganization was impressive, it likely would have been impossible without the strong organizational and technical base that already existed at the company.

construct such lists, we searched for comprehensive lists of innovations constructed by others which identified the major innovations, the years they were introduced, and the firms responsible for the innovations. Given the difficulty of putting together such lists, they are rarely assembled, and the lists we found differed considerably in their level of detail. The most comprehensive was developed by Abernathy, Clark, and Kantrow (1983) for automobiles and identifies 631 product and process innovations over 1893 to 1981. For tires, we found an unpublished doctoral dissertation by Warner (1966) listing 53 major product innovations over 1895 to 1965. In televisions, we found an unpublished doctoral dissertation by Levy (1981) listing 35 product innovations and 5 process innovations from after World War II to 1979. No list was found for penicillin. For televisions it was possible to supplement the list of process innovations and to put together a comparable list of process innovations for penicillin by searching the relevant technical journals. In the Appendix we detail how our innovation lists were compiled for each product.

The lists and other data we employ, as discussed below, provide crude indicators of the firms most involved in innovation. Reflecting the crudeness of the information available, for the hazard analyses we use the data simply to divide firms into two categories, which we call innovators and noninnovators. For autos and televisions, our lists of innovations were detailed and many different firms were identified as developing one or more innovations. For each firm, we classified it as an innovator in a given year if it had developed at least one innovation in the prior five years. In televisions, our list of innovations ended in 1979, and so in the hazard analysis we consider survival through 1979.

For tires and penicillin, our lists of innovation were not nearly as detailed and only a small number of firms were recorded as innovators. Consequently, the lists were not very useful in distinguishing innovators from noninnovators for the purposes of the hazard analysis. Fortunately, we were able to find an alternative way to distinguish innovators and noninnovators for tires and penicillin. In tires, in 1910 a major new tire design called the cord tire that would eventually take over the entire market was introduced in the U.S. It was steadily improved through a number of innovations, and by 1920 the cord tire accounted for 35% of new tire sales. All the leading firms produced the cord by 1920, and within three years nearly every firm produced the cord. We found a surviving issue for 1920 of an old trade journal called the *Tire Rate Book* which listed tire producers and indicated which ones produced the cord in 1920. Of the 155 firms listed that were also in our producer list, 111 were listed as cord producers, and these were the firms we classified as innovators, with the other 44 classified as noninnovators.[11] In the hazard analysis, we consider the number of years the 155 firms survived after 1920. We also found a 1917 issue of the *Tire Rate Book* that listed the first eight producers of the cord and a 1923 issue that listed the first 21 producers of the balloon tire, which represented a major advance in the cord. We use these tabulations below in our analysis of cohort innovation rates. In penicillin, a major breakthrough was made in synthesizing penicillin in the laboratory around 1958. This opened up a whole new class of penicillin drugs called the semisynthetics which had greatly enhanced therapeutic powers. Using the annual editions of the trade register we employed to construct the list of penicillin producers, we identified the firms in the industry in 1959 that subsequently produced one or more of the semisythetics, which were classified as the innovators, with all other firms classified as noninnovators. In the hazard analysis, we consider the number of years the 1959 producers survived after 1959.

[11] See Klepper and Simons (1999) for a more detailed discussion of the cord tire and the data, and for a more thorough analysis of the relationship between cord tire production in 1920 and length of survival after 1920.

Before reporting our analyses, it is useful to reflect on what we should expect to see if the longer survival of earlier entrants were related to innovation, and more generally if innovation were a key force contributing to the shakeouts. The competitive advantage theory provides a useful way of thinking about these issues. It implies that the length of firm survival is determined by a firm's rate of innovation, and in turn that the firm's innovation rate is determined by when it entered and its R&D productivity. If entry cohorts have comparable distributions of firms in terms of R&D productivity,[12] the theory predicts: 1) the average number of innovations per firm, and hence the likelihood of a firm being an innovator in any given period, is greater for earlier entrants; 2) within each cohort of entrants, those with greater R&D productivity have a higher rate of innovation and survive longer, hence within a cohort the hazard should be lower for firms identified as innovators; 3) across cohorts, the hazard should be lower for earlier entrants because they reap a greater return from innovation due to their greater size.

The first prediction can be evaluated using the tabulations reported in Table 6. Using the lists of innovations for each product, the number of innovations per firm over the 20 years following the peak number of producers is computed, where only firms that produced some time in this 20-year period are considered.[13] These figures are then averaged across the firms in each of the three entry cohorts defined in the prior section, which yields average rates of innovation per firm in each entry cohort. For the cord and balloon tire designs and for the semisynthetic penicillin tabulation, the fractions of firms in each cohort that produced the products in the

[12] The theory actually predicts that the firms in later entry cohorts have greater average R&D productivity because the hurdle they must face to be able to enter profitably is greater than earlier entrants. If this were taken into account, the empirical results reported below would suggest even stronger support for the predictions of the theory.

[13] We wanted to compute innovation rates for all firms over the same time period to control for different rates of innovation over time in each industry. We chose the 20-year period following the peak number of firms so that we

relevant years (1917, 1920, and 1923 for tires, 1959 for penicillin) are listed.[14] The tabulations provide strong support for the first prediction of the competitive advantage theory. In every instance, the rates of innovation were greater the earlier the entry cohort. Indeed, the first cohort's innovation rate was often many times greater than the other two cohorts' innovation rates, indicating that in each industry innovation was dominated by the earliest entrants. The p-values in the right column were computed using Fisher's exact test to compare the fraction of firms in each cohort that developed one or more innovations in the 20 years following the peak number of firms, or in the case of the cord and balloon tire listings and the semisynthetic penicillin listing, the fraction of firms producing the products.[15] The p-values are generally below .05, indicating the innovation rates were significantly different in the cohorts.

The other two predictions are evaluated by estimating hazard models which control for time of entry and whether a firm was an innovator (based on our classification). Given the low rates of innovation in cohorts 2 and 3 as reflected in Table 6, these cohorts were combined. Thus, two entry cohorts are distinguished for each product, an early and a late one. No variables associated with the timing of the shakeout are included both to keep the analysis simple and because of the limited effects these variables had on the hazard in the prior section. For each product, the hazard of firm i in year t, r_{it}, was specified as:

(3) $$r_{it} = h(age_{it}) \exp\{\beta_1 I1_{it} + \beta_2 I2_{it} + \beta_3 NI2_{it}\},$$

---

would include all firms that produced sometime during the shakeout, with 20 years chosen to have a sufficiently long period over which to compute the firm innovation rates.

[14] No figures are provided for tire producers in cohort 3 because the data are limited to 1920 producers and cohort 3 begins with entrants in 1923. To compensate for having only two cohorts, the first cohort is subdivided into two and separate figures on adoption rates are provided for each. No figures are provided for penicillin producers in cohorts 2 and 3 because no firms that entered in cohorts 2 and 3 survived to 1959.

[15] Fisher's exact test is directly applicable to the adoption rates in tires and penicillin. For the innovation listings, firms that survived longer would be more likely to develop one or more innovations over the 20-year period following the peak number of producers, all else equal. Since the earlier entrants survived longer on average, this would cause the p-values associated with Fisher's exact test to overstate the strength of the differences across cohorts.

where age_{it} is the age of firm i in year t, $I1_{it}$ is 1-0 dummy equal to 1 if firm i was in cohort 1 and classified as an innovator for year t, $I2_{it}$ is a 1-0 dummy equal to 1 if firm i was in cohort 2 or 3 and classified as an innovator for year t, $NI2_{it}$ is a 1-0 dummy equal to 1 if firm i was in cohort 2 or 3 and was *not* classified as an innovator for year t, and the model was estimated alternatively using the exponential hazard $h(age_{it}) = \exp\{c\}$, which assumes the hazard is independent of age, and the Cox proportional hazards model, which allows the hazard to take on a different value for each (integer) age. The model allows innovators to have a different hazard than noninnovators in each cohort and also allows the time of entry to affect the hazard differently for innovators and noninnovators, with the omitted reference group noninnovators in cohort 1. For autos and televisions, the dummy variables for each firm vary over time according to whether they have innovated in the last five years, which effectively allows an innovation to affect the hazard for five years. If innovation lowers the hazard for all entry cohorts, β_1 and β_2 - β_3 should be negative, and if earlier entry lowers the hazard then β_1 - β_2 should be negative and β_3 positive.

Maximum likelihood estimates of the coefficients computed using Stata are reported in Table 7. They are similar for the exponential and Cox models. All the coefficient estimates conform with the predictions. Across the four products and the two sets of estimates, the hazard of innovators is estimated to be 51% to 91% lower than noninnovators in cohort 1 and 48% to 82% lower than noninnovators in the combined cohorts 2 and 3, with nearly all the differences significant. This conforms strongly with the second prediction of the competitive advantage theory. Across the three relevant products (there are no firms in cohorts 2 and 3 in penicillin, so no comparison can be made), the hazard is estimated to be 55% to 82% lower for innovators in cohort 1 than in the combined cohorts 2 and 3, with the difference significant in tires, and 11% to 58% lower for noninnovators in cohort 1 than the combined cohorts 2 and 3, with the difference significant in autos and tires. This conforms strongly with the third prediction of the competitive advantage theory.[16] Indeed, for two of the products, the hazard of innovators in the combined cohorts 2 and 3 is estimated to be lower than for noninnovators in cohort 1 (the omitted group), with one of the differences significant, and in the third product there is little difference between the hazards of the respective groups. Thus, innovation was sufficiently important that it could compensate for the disadvantages of later entry relative to earlier entrants that did not innovate.

These results suggest that the advantage of early entry was directly related to innovation. The early entrants had much greater rates of innovation than later entrants, and firms that innovated had much lower hazards than noninnovators, which together imparted a substantial advantage to earlier entrants. More generally, the results suggest that innovation played a key role in conditioning the competitive process in each product, including the dramatic shakeouts that each experienced.

V. Conclusions

We investigated the nature of the firm survival patterns in four new products that experienced severe shakeouts despite continued growth in output and little change in the geographic scope of their markets. Two patterns in the hazard analyses were particularly notable. First, by the time of each of the shakeouts, the earliest entrants had a markedly lower hazard, and this persisted for many years thereafter. Second, firm hazards declined with age in

---

[16] Note that time of entry had a more pronounced effect on the hazard for innovators than noninnovators, which is consistent with time of entry operating through its effect on incentives to innovate (via its effects on firm size).

autos and tires, the two products with the greatest diversity among early entrants, whereas there was no sign of any effect of age on the hazard in penicillin and mixed evidence of age dependence in televisions. Together, these patterns suggest a competitive process in which early entry confers a competitive advantage and firms differ in terms of their fitness. Our findings concerning innovation suggest that the advantage of early entry was related to the greater proclivity of early entrants to innovate and differences across firms in terms of their fitness were linked to their ability to innovate.

What do these patterns and others that did not occur reveal about each of the theories? Consider first the event theories. The radical invention theory predicts an initial advantage of early entrants at the outset of the shakeout, although this prediction is primarily an assumption rather than an implication of the theory. The main implications of the theory involve the ramifications expected to emanate from the technological development triggering the shakeout. The theory predicts an initial rise in cohort hazard rates that dissipates over time, leading to a convergence in cohort hazard rates. There is some evidence of a rise in the hazard at the start of the shakeout and then a subsequent fall in the hazard in one or two of the products, but almost no sign of the convergence in cohort hazard rates predicted by the theory. The dominant design theory is somewhat vague in its implications regarding firm survival, although we interpreted its logic as implying similar patterns to the radical invention theory. It does predict that experienced firms will have a lower hazard at the start of the shakeout, although the logic of the theory suggests that experience involving older technologies rendered obsolete by the dominant design could actually be detrimental. Our findings certainly do not support this more nuanced view of the theory—firms that entered later but prior to the shakeout and presumably the emergence of the dominant design had much higher hazards during the shakeout than the earliest entrants.

Whether the dominant design view can be reconciled with the earliest entrants having a persistently lower hazard for many years after the start of the shakeouts is less clear given the absence of a formal model from which to derive testable implications.

The evidence is considerably more favorable to the competitive advantage theory. The persistently lower hazard of the earliest entrants after the start of the shakeouts and the dominance of both sales and innovation by the earliest entrants are in accord with the predictions of the theory. The age dependence of the hazard in autos and tires and the strong relationship between the firm hazard and innovation are also in accord with the theory. But the cohort hazard patterns are more varied than implied by the theory, as evidenced by the eventual convergence of the cohort hazards in tires and the initial convergence and then divergence of the cohort hazards in televisions, and there is some sign of a rise in the hazard at the start of some of the shakeouts that is not addressed by the theory. But overall, the patterns provide considerable support for the theory.

Our interpretation of the findings is consistent with our detailed investigation of technological change in the four products in Klepper and Simons (1997). We found instances of major innovations such as color TV and the semisynthetic penicillins that apppear to have had significant competitive ramifications, consistent with the premise of the radical invention theory. We also found some evidence of increasing attention being devoted to improving the production process over time, as predicted by the dominant design theory. But we did not find these developments distinctively concentrated around the start of the shakeouts in the products. Indeed, one of our main conclusions was that for a number of reasons even the most important technological improvements had limited competitive ramifications and it seemed doubtful that any of the shakeouts could be attributed to any one technological development. We found that the products were characterized by continual technical challenges and firms had to continually keep up with these challenges in order to maintain their leadership. Our findings here concerning firm survival and innovation clearly indicate that the earliest entrants were best able to address these challenges. The shakeouts in each of the products appear to be a byproduct of a competitive process in which the earliest entrants came to dominate their markets by continually being in the vanguard of innovation.

APPENDIX

In this Appendix, we describe sources and procedures used to construct the panel data set of firm production and technological change. Decisions made to ensure that the data remain consistent across periods of time are catalogued. Alternative data sources for production data in each product are briefly compared to the sources used.

Firm Production

In automobiles, the list of manufacturers used is based on list A compiled by Smith (1968, pp. 191-267). His additional list B includes firms that likely never produced the product, and hence list A alone was used. Smith also included information used to detect which makes were produced by a single firm and to code mergers and acquisitions. A more extensive source is the *Standard Catalog of American Cars* in three volumes, beginning with Kimes and Clark

(1996). This source includes many firms that never produced automobiles, and hence was not used. Entry and exit patterns based on Smith broadly agree with other sources, except that two sources which leave out many of the smaller and earlier producers date the peak number of firms in 1921 or 1922 (Simons, 1995, pp. 42-45).[17]

In tires, the list of manufacturers and their dates of production was taken from consecutive issues of a trade directory, *Thomas' Register of American Manufacturers*. With the exception of a few early years in which editions of the *Register* were not published, annual data were used from the volumes dated 1905 through 1981, after which the definition of the *Register*'s tire categories changed.[18] Data collected were matched as closely as possible to the categories of automobile pneumatic and cushion tires, excluding solid tires which pertained to a substantially different market.[19] Cushion tire producers were few in number and were included in part because of difficulty distinguishing them from pneumatic tire producers. Among tire producers listed in the 1905 or 1906 volumes of *Thomas' Register*, entry dates before 1905 were identified using the 1901 through 1903 issues of another annual trade register, *Hendrick's Commercial Register of the United States for Buyers and Sellers* (the 1904 issue could not be obtained). Time-series data in French (1986, p. 33; 1991, p. 48) confirm the approximate date of the shakeout, with his data on the number of firms or on entry/exit respectively suggesting that the peak number of firms occurred either by 1919-1921 or in 1921. Information on mergers and

---

[17] Utterback and Suárez use a list of automobile producers compiled by Richard H. Fabris (1966), but this source excludes all makes of cars that lasted fewer than five years or that ceased production before 1924, making it impossible to analyze exit before 1924.

[18] The date at which firms produced tires and penicillin was in most years assumed to be one year earlier than the date printed on the cover of *Thomas' Register* based on copyright dates printed in the registers and on discussions with the publisher.

[19] In the 1905 through 1909/10 editions, data come from the category Tires. In the 1912 through 1921 editions, data come from the categories Tires: Auto. Misc.; Tires: Rubber, Auto., Vehicle, Etc., Pneumatic; Tires: Rubber, Auto., Vehicle, Etc., Cushion; and (excluding 1912) Tires: Leather Pneumatic. In 1922/23 on, data come from the category Tires & Tubes: Rubber, Automobile, Vehicle, Etc., Pneumatic. In early years, firms indicated as producing only carriage, bicycle, or train tires were excluded.

acquisitions of tire manufacturers was drawn from Gettell (1940), Epstein (1949), Bray (1959), FTC (1966), Dick (1980), French (1991), a Uniroyal internal document kindly provided by French, and surviving issues of a trade periodical, the *Tire Rate Book*, from the 1920s.

In televisions, lists of manufacturers were taken from *Television Factbook*, a trade volume published at first quarterly, then semiannually, and later annually, that listed TV set manufacturers from 1948 through 1989. The *Factbook* initially listed kit makers separately from manufacturers of assembled sets, and the kit makers category was combined with listings of assembled set manufacturers to ensure comparability of the data over time. In Figure 1, a count of 31 firms was used for 1947 based on a reference in the 17 January 1948 issue of *Television Digest and FM Reports* (p. 1) to Supplement 57, which listed TV set manufacturers. (The supplement itself could not be obtained despite the publisher's kind efforts.) To construct entry and exit data for televisions in Figure 1, the entry and exit figures were divided by the appropriate time interval, which could be as small as 0.25 year, so that all numbers are measured in comparable units of a number of firms per year. An analogous procedure was used for two-year gaps in the publication of *Thomas' Register* for tires and the *Television Factbook* for TVs (only one issue of the *Factbook* was published in 1962 and 1963 and we did not obtain volume 51). For hazard analyses, lists of producers from multiple issues in a single year were combined and treated as a single annual list. A list of TV set and parts producers in *Thomas' Register* suggests the peak number of producers was reached in 1950, one year earlier than indicated in the *Factbook* data. Among television producers listed in the 1949 volume of the *Television Factbook*, entry dates before 1949 were identified according to when they were first listed as a producer in *Television Digest and FM Reports*, which was first published in 1945. Information on mergers and acquisitions of TV set manufacturers was drawn from Datta (1971), Levy (1981), Willard (1982), LaFrance (1985), and Teitelman (1994).

In penicillin, lists of manufacturers were combined from annual editions of *Thomas' Register* and *Synthetic Organic Chemicals* pertaining to producers in 1944-1992, since each source by itself was incomplete, plus 1943 manufacturers were catalogued based on FTC (1958). One relevant acquisition was noted using FTC (1958).

Innovation

A list of automobile product and process innovations was drawn from Abernathy, Clark, and Kantrow (1983). Innovations were attributed to specific firms, or in a few cases to multiple firms. For each firm in our data we recorded its associated number of product and process innovations in each year. The list ranked all innovations subjectively in terms of their impact on the manufacturing process, and using rankings rather than counts as a proxy for the importance of innovations yielded similar conclusions.

Adoption of cord and balloon tire designs was catalogued using surviving issues of a trade periodical, the *Tire Rate Book*, from 1917 and the 1920s. The data are described further in Klepper and Simons (1999). A list of tire product innovations was drawn from Warner (1966).

A short list of TV product innovations was drawn from Levy (1981). No existing source had catalogued TV process innovations, and we collected our own data. Process innovations in TV set manufacturing were recorded based on articles from 1946-1970 cited in the *Industrial Arts Index* (later the *Applied Science and Technology Index*), which comprehensively indexes articles in most substantial journals in electronics and other industrial trades. All new manufacturing techniques described for televisions (excluding components) in U.S. firms were catalogued along with the date of innovation or publication, the identity of the innovator, and a 1-7 point subjective estimate of impact on manufacturing costs. Since trade journals actively solicited manufacturing process suggestions, and publications were a source of prestige for the individuals and firms involved, even the smallest firms appear to have had an incentive to publish information about process improvements. Of approximately 210 relevant indexed articles, 198 were obtained and analyzed, yielding a list of 264 process innovations by US firms. In many cases multiple firms were credited with an innovation, and credit was divided evenly among the firms. Using rankings rather than counts to estimate the importance of innovations yielded similar conclusions.

Producers of semisynthetic penicillins were catalogued using annual editions of the trade register *Synthetic Organic Chemicals* (firms listed only in *Thomas' Register* were excluded from analyses of innovation). Firms were classified as innovators beginning in the first year they produced semisynthetic penicillins. Process-related mentions of the name of a firm, in the context of any sort of manufacturing process innovation, were recorded using trade articles identified in the *Industrial Arts Index*, as for televisions, for all years in the sample. From 117 articles obtained and analyzed, 44 mentions were found of US penicillin manufacturers in the context of penicillin process innovations, all in the years 1943-1978.

REFERENCES

Abernathy, William J.; Clark, Kim B. and Kantrow, Alan M. *Industrial Renaissance: Producing a Competitive Future for America*. New York: Basic Books, 1983.

Bray, Warren C. *A History of Capital Development in the American Tire and Rubber Industry.* PhD dissertation, New York University, 1959.

Carroll, Glenn R., and Hannan, Michael T. "Density Delay in the Evolution of Organizational Populations: A Model and Five Empirical Tests." *Administrative Science Quarterly,* 1989, 34, pp. 411-430.

Christensen, Clayton M.; Suárez, Fernando F. and Utterback, James M. "Strategies for Survival in Fast-Changing Industries." *Management Science,* December 1998, *44* (12-2), pp. S-207-220.

Class Journal Company. *The Tire Rate Book*. New York: Class Journal Company, 1917, 1920, 1923.

Dasgupta, Partha and Stiglitz, Joseph. "Learning-by-Doing, Market Structure and Industrial and Trade Policies." *Oxford Economic Papers*, June 1988, *40* (2), pp. 246-268.

Datta, Yudhishter. *Corporate Strategy and Performance of Firms in the U.S. Television Set Industry*. PhD dissertation, State University of New York at Buffalo, 1971.

Dick, J.S. "How Technological Innovations Have Affected the Tire Industry's Structure." *Elastomerics,* September 1980, *112*, pp. 43-48.

Epstein, Ralph C. *Concentration and Price Trends in the Rubber Tire Industry, 1930-47*. Study submitted to the Federal Trade Commission, 1949.

Fabris, Richard H. *A Study of Product Innovation in the Automobile Industry during the Period 1919-1962*. PhD dissertation, University of Illinois, 1966.

Federal Trade Commission. *Report on the Motor Vehicle Industry.* Washington, D.C.: U.S. Government Printing Office, 1939.

Federal Trade Commission. *Economic Report on Antibiotics Manufacture*. Washington, D.C.: U.S. Government Printing Office, 1958.

Federal Trade Commission. *Economic Report on the Manufacture and Distribution of Automotive Tires*. Washington, D.C.: U.S. Government Printing Office, 1966.

Flaherty, Therese. "Industry Structure and Cost-Reducing Investment." *Econometrica*, July 1980, *48* (5), 1187-1209.

French, Michael J. "Structural Change and Competition in the United States Tire Industry, 1920-1937." *Business History Review*, Spring 1986, *60*, pp. 28-54.

French, Michael J. *The U.S. Tire Industry*. Boston: Twayne Publishers, 1991.

Gaffey, John D. *The Productivity of Labor in the Rubber Tire Manufacturing Industry*. New York: Columbia University Press, 1940.

Gettell, Richard. *Pluralistic Competition: With an Illustrative Case Study of the Rubber Tire Industry*. PhD dissertation, Univ. of California at Berkeley, 1940.

Gort, Michael and Klepper, Steven. "Time Paths in the Diffusion of Product Innovations." *Economic Journal,* September 1982, *92* (3), pp. 630-653.

Gunnell, John. *Standard Catalog of American Cars 1946-1975*, 3rd ed. Iola, Wis.: Krause Publications, 1992.

Huber, Peter J. “The Behavior of Maximum Likelihood Estimates under Nonstandard Conditions,” in *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*. Berkeley, Ca.: University of California Press, 1967, pp. 221-233.

Jovanovic, Boyan and MacDonald, Glenn. “The Life Cycle of a Competitive Industry.” *Journal of Political Economy*, 1994, *102*, pp. 322-347.

Kimes, Beverly Rae and Clark, Henry Austin Jr. *Standard Catalog of American Cars 1805-1942*, 3rd ed. Iola, Wis.: Krause Publications, 1996.

Klepper, Steven. “Entry, Exit, Growth, and Innovation over the Product Life Cycle.” *American Economic Review*, June 1996, *86* (3), pp. 562-583.

Klepper, Steven. “Firm Survival and the Evolution of Oligopoly.” Unpublished manuscript, Carnegie Mellon University, 1999.

Klepper, Steven and Graddy, Elizabeth. “The Evolution of New Industries and the Determinants of Market Structure.” *RAND Journal of Economics*, 1990, *21*, pp. 27-44.

Klepper, Steven and Simons, Kenneth L. “Technological Extinctions of Industrial Firms: An Inquiry into their Nature and Causes.” *Industrial and Corporate Change*, March 1997, *6* (2), pp. 379-460.

Klepper, Steven and Simons, Kenneth L. “The Making of an Oligopoly: Firm Survival and Technological Change in the Evolution of the U.S. Tire Industry.” Unpublished manuscript, Carnegie Mellon University and Royal Holloway College of the University of London, 1999.

LaFrance, Vincent. *The United States Television Receiver Industry: United States Versus Japan, 1960-1980*. PhD dissertation, Pennsylvania State University, 1985.

Levy, Jonathan. *Diffusion of Technology and Patterns of International Trade: The Case of Television Receivers*. PhD disseration, Yale University, 1981.

Lin, D.Y. and Wei, L.J. “The Robust Inference for the Cox Proportional Hazards Model.” *Journal of the American Statistical Association*, December 1989, *84* (408), pp. 1074-78.

Metcalfe, J. S. and Gibbons, M. “Technology, Variety and Organisation: A Systematic Perspective on the Competitive Process,” in Richard S. Rosenbloom and Robert A. Burgelman, eds., *Research on Technological Innovation, Management, and Policy*, vol. 4. Greenwich, Conn.: JAI Press, 1988, pp. 153-93.

Nelson, Richard R. and Winter, Sidney G. “Forces Generating and Limiting Concentration under Schumpeterian Competition.” *Bell Journal of Economics*, 1978, *9*, pp. 524-48.

Oxenfeldt, Alfred R. *Marketing Practices in the TV Set Industry*. New York: Columbia University Press, 1964.

Radio News Bureau. *Television Digest and FM Reports*. Washington, D.C.: Radio News Bureau, 1945-1950.

Reynolds, Lloyd G. “Competition in the Rubber-Tire Industry.” *American Economic Review*, 1938, *3*, pp. 459-468.

Samuel E. Hendricks Co. *Hendrick’s Commercial Register of the United States for Buyers and Sellers*. New York: Samuel E. Hendricks Co., 1901-1903.

Schwartzman, David. *Innovation in the Pharmaceutical Industry*. Baltimore: Johns Hopkins University Press, 1976.

Shaked, Avner and Sutton, John. “Product Differentiation and Industry Structure.” *Journal of Industrial Economics*, December 1987, *36* (2), pp. 131-146.

Simons, Kenneth L. *Shakeouts: Firm Survival and Technological Change in New Manufacturing Industries*. PhD dissertation, Carnegie Mellon University, 1995.

Smith, Philip H. *Wheels within Wheels: A Short History of American Motor Car Manufacturing*. New York: Funk and Wagnalls, 1968.

Suárez, Fernando and Utterback, James. "Dominant Designs and the Survival of Firms." *Strategic Management Journal*, June 1995, *16* (5), pp. 415-430.

Sutton, John. *Technology and Market Structure*. Cambridge, Mass.: MIT Press, 1998.

Teitelman, Robert. *Profits of Science*. New York: Basic Books, 1994.

Thomas Publishing Company. *Thomas' Register of American Manufacturers*. New York: Thomas Publishing Company, 1905-1993.

U.S. Tariff Commission (later U.S. International Trade Commission). *Synthetic Organic Chemicals*. Washington, D.C.: U.S. Government Printing Office, 1944-1992.

Utterback, James and Suárez, Fernando. "Innovation, Competition, and Industry Structure." *Research Policy*, 1993, *22*, pp. 1-21.

Warren Publishing Co. *Television Factbook.* Washington, D.C.: Warren Publishing Co., 1949-1989.

Warner, Stanley L. *Innovation and Research in the Automobile Tire and Tire-Supporting Industries*. PhD dissertation, Harvard University, 1966.

White, Halbert. "Maximum Likelihood Estimation of Misspecified Models." *Econometrica*, January 1982, *50* (1), pp. 1-25.

Willard, Gary E. *A Comparison of Survivors and Non-Survivors under Conditions of Large-Scale Withdrawal in the U.S. Color Television Set Industry*. PhD dissertation, Purdue University, 1982.

Figure 1.—Number of Producers, Entry, and Exit in the Four Products

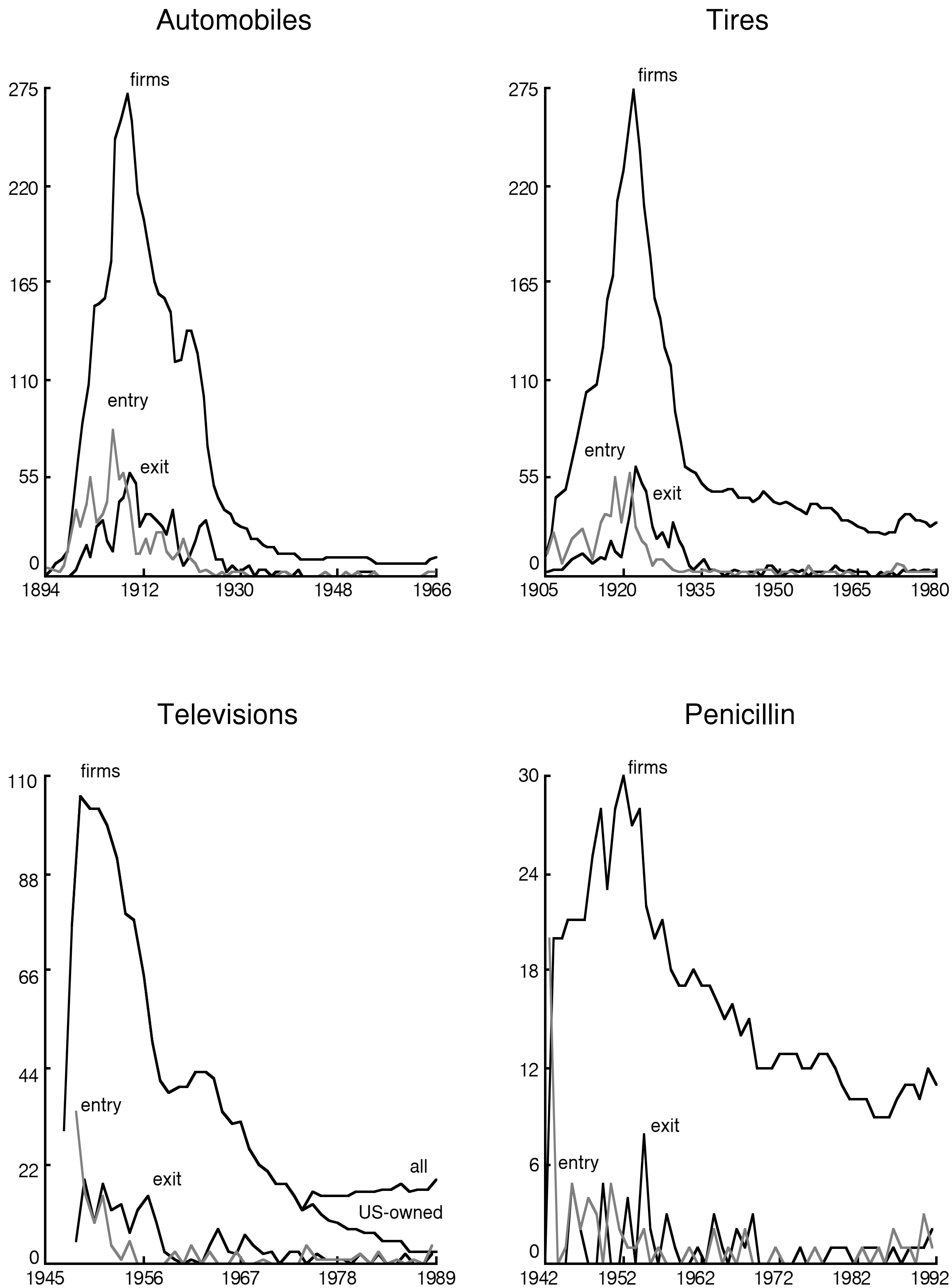

Figure 2a.—Smoothed Hazard Plot for Automobiles

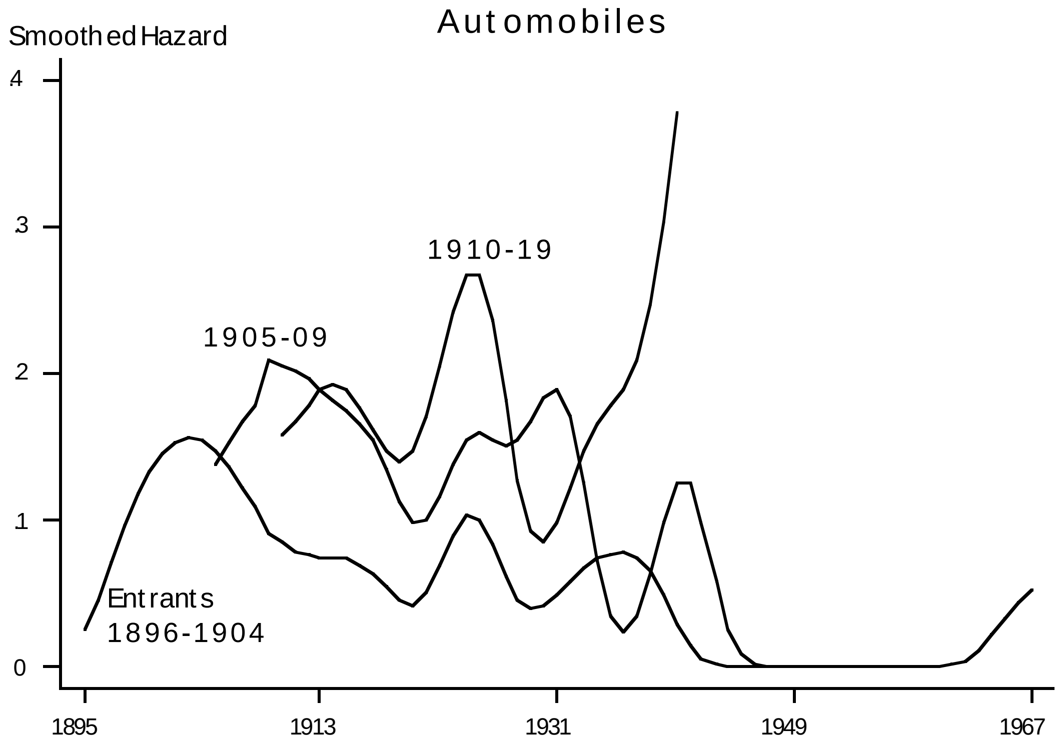

Figure 2b.—Smoothed Hazard Plot for Tires

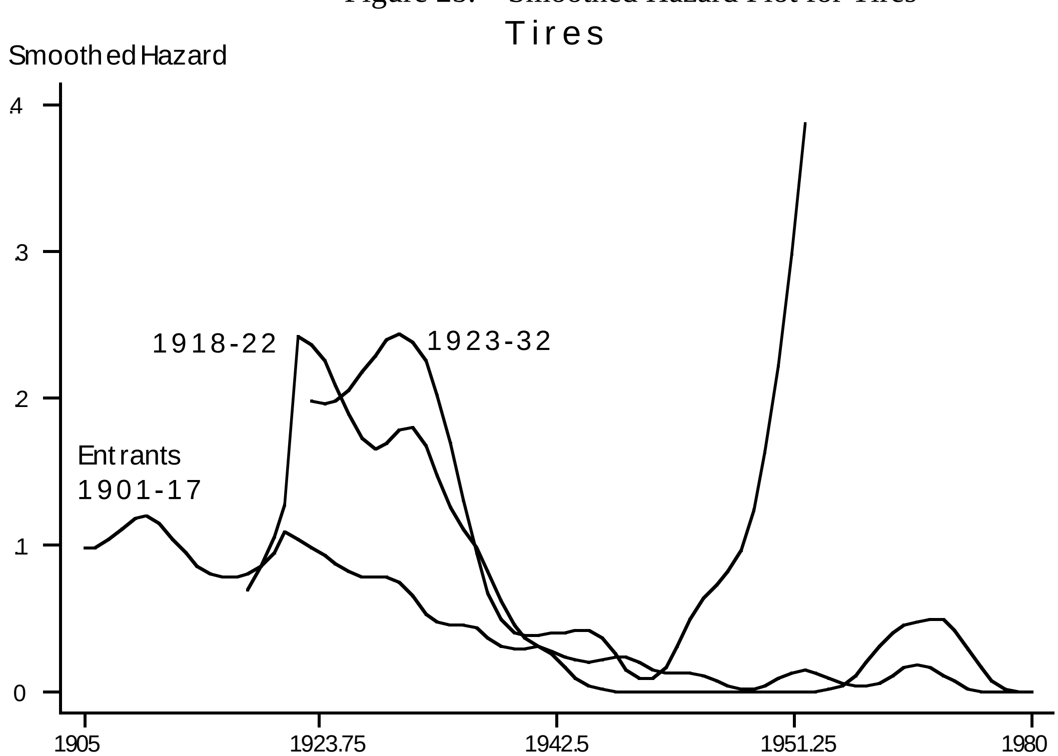

Figure 2c.—Smoothed Hazard Plot for Televisions

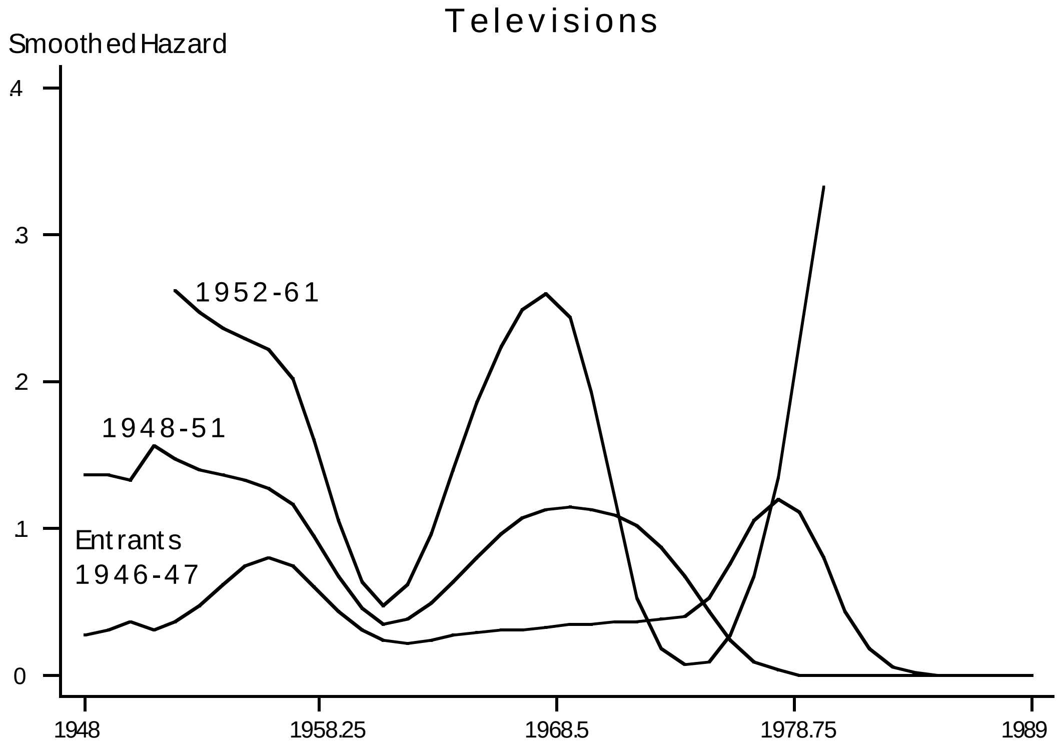

Figure 2d.—Smoothed Hazard Plot for Penicillin

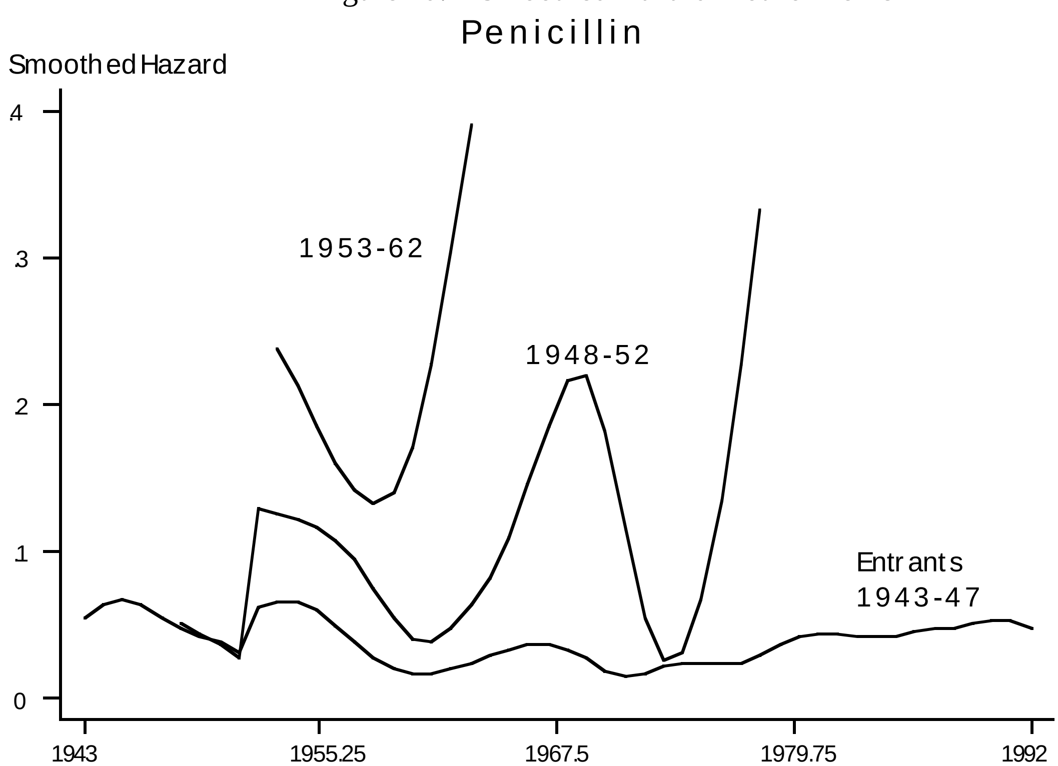

Table 1.— Years (Number of Firms) in the Three Entry Cohorts

Product	Cohort 1	Cohort 2	Cohort 3
Autos	1895-1904 (220)	1905-1909 (269)	1910-1919 (183)
Tires	1901-1917 (239)	1918-1922 (224)	1923-1932 (84)
Televisions	1946-1947 (22)	1948-1951 (113)	1952-1961 (28)
Penicillin	1943-1947 (28)	1948-1952 (13)	1953-1962 (4)

Table 2.— Predictions of the Three Theories

Parameter	Event theory 1 (radical invention)	Event Theory 2 (dominant design)	Competitive Advantage Theory
β_1	+	+	0
β_2	+, < β_3	- or < β_3	+, < β_3
β_3	+	+	+
$\beta_1 + \beta_2$	+	+	+
$\beta_1 + \beta_3$	+	+	+
β_4	-	-	0
β_5	-, > β_6	+ or > β_6	≥ 0
β_6	-	-	≥ 0
$\beta_4 + \beta_5$	-	-	≥ 0
$\beta_4 + \beta_6$	-	-	≥ 0
Age	?	?	≤ 0

Table 3.—Hazard of Exit: Entry Time and Shakeout

Exponential Model

		Automobiles		Tires		Televisions		Penicillin	
Constant	c	-2.08	(0.08)	-2.66	(0.09)	-2.37	(0.16)	-3.09	(0.25)
S_t	β_1	-0.23	(0.25)	0.47*	(0.21)	-0.52	(0.48)	0.31	(0.65)
$Cohort2_i\ S_t$	β_2	0.83**	(0.26)	0.83***	(0.22)	1.23*	(0.49)	0.72	(0.84)
$Cohort3_i\ S_t$	β_3	0.42	(0.30)	0.71*	(0.29)	1.75**	(0.58)	0.46	(1.60)
S_t (t-S)	β_4	-0.06†	(0.04)	-0.06†	(0.03)	-0.03	(0.07)	-0.07	(0.09)
$Cohort2_i\ S_t$ (t-S)	β_5	0.01	(0.04)	0.00	(0.04)	-0.09	(0.07)	0.02	(0.12)
$Cohort3_i\ S_t$ (t-S)	β_6	0.08†	(0.04)	0.05	(0.05)	-0.06	(0.08)	0.18	(0.18)
	$\beta_1 + \beta_2$	0.60***	(0.13)	1.30***	(0.14)	0.71**	(0.23)	1.03†	(0.62)
	$\beta_1 + \beta_3$	0.19	(0.19)	1.18***	(0.23)	1.23**	(0.39)	0.78	(1.49)
	$\beta_4 + \beta_5$	-0.06**	(0.02)	-0.06**	(0.02)	-0.11**	(0.04)	-0.05	(0.08)
	$\beta_4 + \beta_6$	0.02	(0.02)	-0.01	(0.03)	-0.09†	(0.05)	0.11	(0.16)
Log Likelihood		-1826.04		-1587.39		-456.46		-151.06	

Weibull Model

		Automobiles		Tires		Televisions		Penicillin	
Constant	c	-2.34	(0.09)	-2.59	(0.10)	-2.46	(0.21)	-3.08	(0.45)
Age parameter	ln p	0.10*	(0.04)	-0.02	(0.04)	0.03	(0.07)	-0.00	(0.12)
S_t	β_1	-0.30	(0.26)	0.48*	(0.21)	-0.52	(0.48)	0.31	(0.65)
$Cohort2_i\ S_t$	β_2	0.99***	(0.27)	0.78***	(0.23)	1.25*	(0.49)	0.72	(0.84)
$Cohort3_i\ S_t$	β_3	0.71*	(0.31)	0.64*	(0.30)	1.83**	(0.61)	0.45	(1.71)
S_t (t-S)	β_4	-0.07†	(0.04)	-0.06†	(0.03)	-0.03	(0.07)	-0.07	(0.09)
$Cohort2_i\ S_t$ (t-S)	β_5	-0.01	(0.04)	0.01	(0.04)	-0.09	(0.07)	0.02	(0.12)
$Cohort3_i\ S_t$ (t-S)	β_6	0.07†	(0.04)	0.05	(0.05)	-0.07	(0.08)	0.18	(0.19)
	$\beta_1 + \beta_2$	0.69***	(0.13)	1.26***	(0.13)	0.73**	(0.23)	1.03†	(0.62)
	$\beta_1 + \beta_3$	0.41*	(0.19)	1.12***	(0.23)	1.31**	(0.43)	0.77	(1.62)
	$\beta_4 + \beta_5$	-0.08***	(0.02)	-0.05*	(0.02)	-0.12**	(0.04)	-0.05	(0.09)
	$\beta_4 + \beta_6$	-0.00	(0.02)	-0.01	(0.03)	-0.10†	(0.05)	0.11	(0.17)
Log Likelihood		-940.34		-824.60		-245.44		-69.33	

Cox Model

		Automobiles		Tires		Televisions		Penicillin	
S_t	β_1	-0.21	(0.28)	0.37	(0.25)	-0.32	(0.60)	1.74	(1.09)
$Cohort2_i\ S_t$	β_2	0.53†	(0.30)	0.48†	(0.28)	1.37*	(0.57)	-0.42	(1.09)
$Cohort3_i\ S_t$	β_3	0.24	(0.35)	0.35	(0.36)	1.28†	(0.68)	-1.80	(2.35)
S_t (t-S)	β_4	-0.06	(0.04)	0.00	(0.04)	-0.07	(0.08)	-0.28*	(0.12)
$Cohort2_i\ S_t$ (t-S)	β_5	0.04	(0.05)	-0.02	(0.05)	-0.09	(0.09)	0.23	(0.15)
$Cohort3_i\ S_t$ (t-S)	β_6	0.08	(0.05)	0.00	(0.05)	0.01	(0.09)	0.50†	(0.27)
	$\beta_1 + \beta_2$	0.32*	(0.12)	0.85***	(0.13)	1.05***	(0.29)	1.31**	(0.47)
	$\beta_1 + \beta_3$	0.03	(0.20)	0.72**	(0.25)	0.96**	(0.34)	-0.07	(1.95)
	$\beta_4 + \beta_5$	-0.02	(0.03)	-0.01	(0.03)	-0.16**	(0.06)	-0.05	(0.11)
	$\beta_4 + \beta_6$	0.02	(0.02)	0.00	(0.04)	-0.06	(0.05)	0.23	(0.23)
Log Partial Likelihood		-3526.05		-2783.02		-613.40		-116.64	

Sample Characteristics

	Automobiles	Tires	Televisions	Penicillin
Number of firms	672	547	163	45
Number of exits	625	511	144	40
Number of firm-years	4474	4848	1394	730

Standard errors are in parentheses. † $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$ (two-tailed).

Table 4.— Cox Age Baseline Estimates at Ages 0-19 and Means for Ten-Year Periods

	Automobiles	Tires	Televisions	Penicillin
Age 0	.097	.077	.148	.057
Age 1	.187	.137	.136	.049
Age 2	.180	.119	.066	.110
Age 3	.171	.126	.035	.057
Age 4	.171	.096	.071	.017
Age 5	.122	.113	.094	.017
Age 6	.128	.076	.045	.032
Age 7	.134	.066	.055	.018
Age 8	.155	.092	.187	.044
Age 9	.171	.069	.195	.022
Age 10	.080	.073	.0	.0
Age 11	.077	.055	.0	.020
Age 12	.100	.099	.167	.026
Age 13	.098	.078	.111	.0
Age 14	.058	.049	.073	.0
Age 15	.210	.054	.157	.096
Age 16	.141	.036	.0	.0
Age 17	.130	.013	.148	.080
Age 18	.113	.056	.208	.116
Age 19	.128	.031	.099	.191
Ages 0-9	.152	.097	.103	.042
Ages 10-19	.113	.054	.096	.053
Ages 20-29	.097	.033	.046	.075
Ages 30-39	.065	.024	.031	.048
Ages 40-49	.0	.010		.037
Ages 50-59	.0	.013		
Ages 60-69		.0		
Ages 70-79		.0		

Table 5.— Firms with Market Shares of 10% or Greater

Product	Firm	Entry Date
Automobiles	T.B. Jeffery / Nash / American Motors	1902
	Buick / General Motors	1903
	Ford Motor Company	1903
	Maxwell-Briscoe / Chrysler	1904
Tires	US Rubber	1901
	Goodrich	1901
	Goodyear	1902
	Firestone	1906
Televisions	RCA	1946
	Admiral	1947
	General Electric	1947
	Motorola	1947
	Philco / Philco-Ford Corp.	1947
	Zenith	1948
Penicillin	American Home Products / Wyeth	1943
	Bristol	1943
	Eli Lilly	1943
	Pfizer / Roerig	1943
	Squibb	1943

Notes: In automobiles, some firms that attained early market share leadership but fell back by the beginning of the 1900s are ignored. In tires, the entry date is the first date recorded in trade registers for production of pneumatic automobile tires. In televisions, a few TV sets were produced beginning in 1938, but this limited pre-World War II production is ignored in determining entry dates. In penicillin, market shares of 10%+ could be assessed only in the years 1960 and 1973.

Sources: Kimes and Clark (1996), Gunnell (1992), French (1986, p. 31), Dick (1980, p. 47), Oxenfeldt (1964, p. 13), Levy (1981, pp. 84-88), *Look National Appliance Survey 1959* (p. 201), Datta (1971, p. 295), Schwartzman (1976, p. 131).

Table 6.—Innovation Rate by Entry Time

<table>
<tr><th>Product</th><th>Innovation type</th><th colspan="2">Cohort 1</th><th>Cohort 2</th><th>Cohort 3</th><th>Fisher’s Exact p</th></tr>
<tr><td>Automobiles</td><td>Product</td><td colspan="2">.08</td><td>.02</td><td>.01</td><td>p < .001</td></tr>
<tr><td>Automobiles</td><td>Process</td><td colspan="2">.03</td><td>.0</td><td>.001</td><td>p = .037 (.072)</td></tr>
<tr><td>Tires</td><td>Cord 1917</td><td>.36</td><td>.08</td><td></td><td></td><td>p = .023</td></tr>
<tr><td>Tires</td><td>Cord 1920</td><td>1.00</td><td>.73</td><td>.62</td><td></td><td>p = .036 (.033)</td></tr>
<tr><td>Tires</td><td>Balloon 1923</td><td>.63</td><td>.16</td><td>.07</td><td></td><td>p < .001</td></tr>
<tr><td>Tires</td><td>Product</td><td colspan="2">.01</td><td>.0</td><td>.0</td><td>p = .002 (.001)</td></tr>
<tr><td>Televisions</td><td>Product</td><td colspan="2">.63</td><td>.07</td><td>.0</td><td>p = .058 (.064)</td></tr>
<tr><td>Televisions</td><td>Process</td><td colspan="2">.02</td><td>.01</td><td>.0</td><td>p < .001</td></tr>
<tr><td>Penicillin</td><td>Semisynthetic</td><td colspan="2">.56</td><td></td><td></td><td></td></tr>
<tr><td>Penicillin</td><td>Process</td><td colspan="2">.05</td><td>.0</td><td>.0</td><td>p = .124 (.049)</td></tr>
</table>

Notes: In tires, the available innovations data require new cohorts, which include entrants in 1901-06 (cohort 1a), 1907-17 (1b), 1918 onward (2). Fisher’s exact test reports the probability of observing inter-cohort differences at least as large as reported here under the null hypothesis that all cohorts share identical probabilities of innovation. Where p-values from this Fisher’s exact test are greater than .001, results are reported in parentheses for a further Fisher’s exact test comparing firms in the earliest cohort versus those in both later cohorts combined.

Table 7.—Hazard of Exit: Entry Time and Innovation

Exponential Model

		Automobiles		Tires		Televisions		Penicillin	
Constant	c	-2.32	(0.11)	-2.50	(0.38)	-2.43	(0.22)	-2.86	(0.33)
Innovator 1	β_1	-2.15***	(0.49)	-0.98*	(0.42)	-2.41*	(1.03)	-1.42†	(0.75)
Innovator 2-3	β_2	-1.05†	(0.59)	0.08	(0.43)	-0.71	(0.70)		
Noninnovator 2-3	β_3	0.66***	(0.13)	0.86*	(0.40)	0.22	(0.25)		
	$\beta_1 - \beta_2$	-1.10	(0.75)	-1.06***	(0.28)	-1.71	(1.23)		
	$\beta_2 - \beta_3$	-1.71**	(0.57)	-0.77***	(0.23)	-0.92	(0.66)		
Log Likelihood		-198.59		-177.23		-74.58		-4.98	

Cox Model

		Automobiles		Tires		Televisions		Penicillin	
Innovator 1	β_1	-1.94***	(0.47)	-0.72*	(0.28)	-2.44*	(1.01)	-1.69*	(0.79)
Innovator 2-3	β_2	-1.02†	(0.58)	0.08	(0.30)	-0.82	(0.67)		
Noninnovator 2-3	β_3	0.57***	(0.12)	0.75*	(0.29)	0.12	(0.25)		
	$\beta_1 - \beta_2$	-0.92	(0.73)	-0.80**	(0.25)	-1.62	(1.20)		
	$\beta_2 - \beta_3$	-1.59**	(0.57)	-0.66**	(0.21)	-0.94	(0.66)		
Log Partial Likelihood		-1258.29		-490.70		-269.29		-9.06	

Sample Characteristics

	Automobiles	Tires	Televisions	Penicillin
Number of firms	298	154	91	9
Number of exits	267	126	73	6
Number of firm-years	2351	2061	852	215

Standard errors are in parentheses. † $p < .10$, * $p < .05$, ** $p < .01$, *** $p < .001$ (two-tailed).