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SPILLOVER EFFECTS OF IP PROTECTION IN THE INTER-WAR AIRCRAFT INDUSTRY

Walker Hanlon
Taylor Jaworski

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ABSTRACT

Can granting IP protection to producers of one good affect the innovation rate in other related goods?To answer this question we exploit a unique policy experiment in the inter-war military aircraft industry. Airframe designs had little IP protection before 1926, but changes passed by Congress in 1926 provided airframe manufacturers with enhanced property rights over the new designs they produced. We show that granting property rights to airframe producers increased innovation in airframes, but slowed down innovation in aero-engines, a complementary good where there was no change in the availability of IP protection. We propose and test a simple theory that explains these patterns.

Walker Hanlon
Department of Economics
NYU Stern School of Business
Henry Kaufman Management Center
44 West Fourth Street
New York, NY 10012
and NBER
walker.hanlon@gmail.com

Taylor Jaworski
Department of Economics, UCB 256
University of Colorado at Boulder
Boulder, CO 80309
and NBER
tjaworski@gmail.com

1 Introduction

Granting property rights for new inventions is a central feature of innovation systems. Standard theories of innovation emphasize how intellectual property (IP) rights incentivize innovation by providing market power. Market power allows firms to extract rents that compensate for investment in innovation. Standard theory also predicts that granting market power to producers of one type of good will impact rents available to firms producing either complementary or substitute goods. A direct implication is that granting IP to one group of producers will change the rents available–and the incentives to innovate–to producers of related goods. This suggests that there may be important spillovers from granting IP protection to goods on innovation activity in complement or substitute goods.

Despite a large literature on IP protection and innovation, there is very little empirical evidence that addresses the potential spillovers of IP protection offered to producers of one type of good on innovation in related goods. Instead, existing research typically focuses on the impact of IP protection within classes of similar products. For example, Williams (2013) and Sampat and Williams (2019) quantify the impact of IP rights on follow-on innovation in human genes and Gilchrist (2016) considers the impact within classes of competing pharmaceutical drugs.[1] In this paper we study spillover effects of IP protection that arise between markets linked by complementary goods produced by different firms.

Research that aims to quantify the direct and spillover effects of IP protection on innovation presents three challenges. The first challenge is to find a setting where IP protection changes for producers of one good, but not for producers of related goods. We focus on one setting, the US aircraft industry during the interwar period, that offers this vital feature. A functional powered aircraft requires both an airframe and one or more aero-engines. In the period we study–and continuing through to today–these two elements are typically produced by different companies and purchased separately (e.g., Boeing produces airframes, while Pratt & Whitney produces engines).

Our study takes advantage of a unique natural experiment during this period. The policy we study originated at the end of World War I, when allegations of war profiteering led Congress to limit the IP rights available to airframe producers of military designs, which represented the vast majority of the aircraft market at that time. Companies that produced a new airframe design did not have an exclusive right to their design. Rather, it was put out for competitive bidding. For example, when the Glenn L. Martin Company designed the MB-3 bomber and the War Department decided to purchase 200 versions of this plane, the production contract was put out for competitive bidding and won by Curtiss, Martin's competitor. The IP regime changed in 1926, when Congress altered the policy to give

[1] See Williams (2017) for a survey of this literature. In addition, a number of papers examine how changes in IP protection affect the price and availability of existing products (e.g., see recent work by Chaudhuri, Goldberg and Jia (2006) and Duggan, Garthwaite and Goyal (2016)). This line of research is different from our study, which focuses on the impact of IP protection on innovation.

firms producing new designs accepted by the military exclusivity in the production contract. Importantly, the change in IP protection only applied to airframe producers while engine producers had access to IP protection over the entire period. This allows us to use this policy to understand the impact of changes in IP protection–by which we mean property rights over a new idea or design–for airframe producers on innovation in both airframes and complementary aero-engines.

A second challenge in studying this question is that standard measures of innovation used in the literature (e.g., patents) critically depend on the IP regime. These cannot be used to track the impact of changes in the IP regime on innovation. Our setting allows us to get around this issue by measuring innovation directly using data on the performance characteristics of the airframes and engines. We draw on a large number of sources to construct standard industry performance measures for airframes (e.g., wing load, calculated as the gross weight per wing area) in distinct market segments (e.g., fighters) as well as for aero-engines (e.g., horsepower per unit of engine displacement).

The third challenge is that changes in airframe or aero-engine innovation in the United States may not be the result of IP policy, but instead reflect broader changes in the world technology frontier that ultimately diffuse to the United States. However, in the interwar period, many countries operated as mostly isolated markets for military aircraft. In each country, the military purchased airframes and engines almost exclusively from domestic producers. While firms in each country were aware of the broader technological trends, they were exposed to different institutional environments. This allows us to compare airframe and aero-engine innovation in the United States before and after the change in IP policy with other countries that did not experience similar changes.

To guide our empirical work, we formalize the incentives to innovate in a simple theoretical model that emphasizes the profit mechanism central to theories of economic growth and innovation (e.g., Romer, 1990; Grossman and Helpman, 1991; Aghion and Howitt, 1992). In our model, the motivation of airframe producers to innovate are the expected profits associated with new invention. When airframe producers do not have access to IP protection, the price of airframes is the perfectly competitive price (consistent with the competitive bidding regime we observe); with IP protection, airframe producers with the best designs can extract additional rents. However, when airframe producers are able to extract greater rents, this reduces the profits available to engine producers and their incentive to innovate.

Our main empirical analysis documents two patterns consistent with the theory. First, after IP protection became available to American airframe producers, the rate of improvement for key performance measures accelerated. This is apparent either when focusing only on changes within the United States over time or comparing the United States to other countries. Prior to 1926, innovation in airframes was typically slower in the United States than in comparison countries; after 1926, the rate of innovation was faster. This suggests that providing IP protection had a positive effect on technological progress in airframes, as predicted by the theory. Second, we find that the rate of innovation in aero-engines slowed after 1926. Again, this pattern appears when looking at the United States over time, as well as relative to available comparisons countries. Since there was no change in the availability of IP protection for engine technology, we attribute this slowdown in the United States to the spillover effects of granting IP protection to airframe producers.

While our results are consistent with the theory, there are alternative stories that can rationalize the pattern of airframe and aero-engine innovation tha we observe. For example, one might worry that these patterns were due to changes in the civil and commercial aircraft market, to changes in the overall level of military expenditures, to other changes in procurement policy, or perhaps because engines and airframe performance were substitutes. We discuss each of these potential alternatives in detail and provide evidence suggesting that they are not likely to be behind the patterns we document.

To provide further support for the profit mechanism proposed in our model, we derive additional testable predictions from theory that can be taken to the data. Specifically, we show that our model predicts that granting IP protection to airframe producers generates incentivizes for mergers between airframe and aero-engine producers, which we refer to as "vertical-complement" mergers.[2] When IP protection allows airframe producers to extract rents for new designs this gives rise to a classic double-marginalization problem, which provides incentives for airframe and aero-engine producers to merge. In the absence of IP protection for airframes, no such problem emerges and therefore there is no incentive for mergers. The model also predicts that mergers should exhibit a particular pattern of matching between airframe and engine producers.

Our setting offers a particularly useful environment for testing this prediction because the permissive antitrust regime meant that firms that wanted to merge faced few regulatory barriers. To test this prediction, we reconstruct histories of all airframe and aero-engine producers through World War II. Prior to the change in 1926 there were two main producers of military-grade aero-engines in the United States: Wright and Pratt & Whitney. By 1929, both had merged with major airframe producers: Wright combined with Curtiss to form Curtiss-Wright Corporation and Pratt & Whitney merged with Boeing as well as several smaller airframe producers to form United Aircraft. We show there was no similar pattern of mergers in the United States before 1926 or after 1930; there was also no similar pattern of mergers between engine and airframe firms in the US civilian market just after 1926, nor do we see a similar pattern of mergers in comparison countries. This suggests mergers between military airframe and aero-engine producers in the United States were linked to the changes in IP protection. Moreover, the pattern of matching between airframe and engine producers that we observe also matches the predictions of the theory.

[2] We use this terminology because, while mergers between aero-engine and airframe producers do not fit the classic definition of a vertical merger, since these inputs were typically purchased separately, they are similar to classic vertical mergers in important ways.

Taken together, our findings make several contributions to the existing literature. First, we provide new evidence for spillover effects from IP protection arising through a link between market power and innovation decisions across markets. This has important implications for understanding the interaction between IP and antitrust policy and, ultimately, the direction of innovation and economic growth. Methodologically, there is a large literature that quantifies the effect of IP protection by comparing similar goods, which may overstate (understate) the effects of IP protection if these goods are complements (substitutes). We also provide the first quantitative assessment of this particular change in IP protection, which has been the subject of debate (Vander Meulen, 1991; Patillo, 1998). In particular, we highlight the role of spillovers in determining the performance characteristics of US aircraft–airframes *and* aero-engines–leading up to World War II.

Second, we contribute to research on the relationship between innovation and market size, including seminal work by Schmookler (1966), and Acemoglu and Linn (2004) and Finkelstein (2004), more recently. In our setting, IP protection for airframes reduces innovation in aero-engines by reducing residual demand. There is also closely related work beginning with Schumpeter (1942) and Arrow (1962) on the effect of competition on innovation. Existing empirical evidence frequently takes competition or market concentration as given and estimates the effect on innovative activity (e.g., Blundell, Griffith and Van Reenen, 1999; Aghion, Bloom, Blundell, Griffith and Howitt, 2005; Aghion, Blundell, Griffith, Howitt and Prantl, 2009; de Bettignies, Gainullin, Liu and Robinson, 2018). Our focus on the effect of IP protection on firms producing complementary goods is novel. In this context, we provide evidence for the endogenous response of market structure to IP protection through vertical-complement mergers.[3]

This paper is also related to the literature on patent pools and compulsory licensing. As we discuss below, there was a patent pool operating in the aircraft industry. However, this patent pool was different from those considered by Lampe and Moser (2010, 2014, 2016). The formation of the pool was compelled by the government largely against the will of the main patent holders. New airframe patents were required to be added to the pool, patent holders received limited remuneration, and firms outside the pool had free access to pool patents when working on government (including military) contracts.[4] In the case of compulsory licensing, recent empirical studies quantify the impact on innovation within the sector where licensing occurred (Moser and Voena, 2012) or on firms with patents licensed in other countries (Baten, Bianchi and Moser, 2017). In contrast, we consider the spillover effects of changes in IP for one good on innovation in other related goods.

[3]See Loury (1979), Vives (2008), and Chen and Sappington (2010), for related theory and Sanyal and Ghosh (2013) for related empirical work that considers changes in patenting by suppliers to the electricity industry following deregulation in the United States during the 1990s. In addition, Klepper (1996), Klepper and Simons (2000), and Buenstorf and Klepper (2009) study innovation and industry evolution in a dynamic framework. Finally, Shapiro (2012), Cohen (2010), and Gilbert (2006) provide overviews of this literature.

[4]See Gilbert (2017) for additional discussion of the impact of patent pools on innovation.

The remainder of this paper is organized as follows. In Section 2 we provide historical background relevant for understanding the setting of the aircraft industry during the interwar period. In Section 3 we present our theory and the predictions we take to the data. Section 4 describes the data and Section 5 describes the empirical analysis and results. We discuss alternative mechanisms in Section 6, historical implications in Section 7, and conclusions in Section 8.

2 Empirical Setting

Military procurement was the primary source of demand for the early aircraft industry, starting with the Wright Brother's first airplane sale to the US Army in 1908. The onset of the First World War dramatically expanded the demand for aircraft, first in Europe and later in the United States.[5] The rapid increase in military aircraft purchases during World War I created enormous profits among companies involved in aircraft production (Holley, 1964, p. 83). In the United States, public disclosure of these profits generated a backlash that led to a Congressional investigation. Anxious to avoid charges of waste, Congress forced military procurement officers to use competitive bidding to allocate aircraft production contracts in the years from the end of the war to 1926. Under this regime, when a company produced a design they were paid a small design fee and the production order was put up for competitive bidding.[6] As a result of this policy, the vast majority of expenditure on aircraft before 1926 was done through competitive bidding. Specifically, of the $22 million spent by the military on aircraft from 1920 to 1924, all but $3 million was allocated through competitive bidding.[7]

World War I also led to the formation of a patent pool, the Manufacturers' Aircraft Association. Most major airframe producers eventually joined the pool, but even those that did not had free access to the patents included in the pool when working on military orders (Bittlingmayer, 1988). The presence of the patent pool essentially eliminated the ability of airframe manufacturers to protect their designs using patents. However, an important feature for our purposes is the fact that the pool did *not* cover aero-engines. For further discussion of the patent pool, see Appendix B.1

The combination of procurement by competitive bidding and inability to seek patent protection meant that in the early 1920s airframe producers often failed to win the production orders for their own designs. An illustration of this is provided by the MB-3 bomber designed by the Glenn L. Martin company towards the end of World War I. Having bought the design rights for a modest sum that did not cover development costs, the War Department decided

[5]See Bryan (2016) for a study of aircraft innovation in the period before 1918.

[6]When one company won the bid for another company's design, the designing company was forced to provide the producer with a prototype together with a set of designs. This effectively ensured that designs could not be protected through secrecy. However, firms could still benefit from process improvements under this regime, so the policy changes we study were unlikely to have substantially altered the benefits of innovations in the production process.

[7](Holley, 1964, p. 84).

to purchase 200 versions of the plane. The contract was put up for competitive bidding. Martin's bid for the production order, which was calculated to include the cost of developing the original design, came in higher than rival companies. As a result, the contract was won by Curtiss Aeroplane and Motor Company. As a consequence, Holley (1964, p. 85) writes,

> *Deprived of his airplane, Martin no longer had any incentive to improve that particular design. Worse yet, deprived of a profitable production contract as a means of reimbursing his earlier investment, Martin was soon unable to finance further development work. The statutes...retarded the pace of research and development.*

This is just one of several examples of a firm failing to win the production order on an aircraft that it had designed. Soon after Curtiss won the MB-3 order, Martin would turn the tables by underbidding Curtiss for the production order of a Navy scout-bomber that Curtiss lost $180,000 designing (Vander Meulen, 1991, p. 62).[8] Clement Keys, the head of Curtiss Aircraft, observed that,

> *It is fairly obvious that no company can spend that amount of money and suffer the grief and disappointment of experimental labor–which is so often lost labor–only to have the product of that labor taken up by the Government and thrown open to competitive bidding. It is fair to say that because of these conditions over which the industry has no control, not only the Curtiss Company, but all other forward looking institutions in this art, have curtailed their efforts, economized their resources and foregone their ambitions for the art in order to adapt themselves to the policies of their Government.* (Vander Meulen, 1991, p. 53).

Not surprisingly, this procurement regime provided airframe producers with little incentive to produce new designs. The military tried to compensate for the lack of innovation incentives by producing their own designs in-house at the Naval Aircraft Factory in Philadelphia and the Army's McCook Field in Ohio. In the end this proved unsatisfactory, possibly because it largely separated design work from manufacturing.

Engines formed an important part of the cost of a complete aircraft. They were also typically produced by a different company than airframes. Consider as an example Boeing's PW-9 pursuit (fighter) aircraft, one of the most successful designs of the 1920s. Army Air Corps Procurement Board records show the total price for a fully equipped PW-9 in 1928 ranged from $30,015 to $31,654. The cost of the airframe alone was quoted at $11,000. This plane was powered by a single Curtiss D-12 engine. The records indicate that D-12's cost

[8] Vander Meulen (1991, p. 62) goes on to describe how Curtiss, "submitted a bid of $32,000 per plane, but Glenn Martin won the contract at $23,000 apiece. Martin complained that the plane came with no blueprints but admitted that they would have been useless in his shop anyway. His staff drew up a new set of blueprints and in the process produced an entirely new plane inferior in performance to the Curtiss design." This story, which was not unusual, highlights how the process of competitive bidding was inefficient in addition to retarding innovation.

around $9,000 at this time. The remaining cost was due to armament, instruments, and other government furnished equipment.

A key feature for our purposes is that the lack of protection for new designs was primarily a problem for airframe manufacturers. For aero-engines, in contrast, the more specialized production process created a concentrated industry with high barriers to entry. Engines were also excluded from the airframe patent pool, which gave engine producers recourse to patent protection. By the mid-1920s, engine production was dominated by a small set of companies, including Wright, Pratt & Whitney, Packard, Lawrence and Curtiss (see Appendix B.6 for market share data).[9] Ultimately, after 1926 and particularly after the mergers of 1929, Wright and Pratt & Whitney would come to dominate this group. As a result of this relatively concentrated market together with access to patent protection, engine manufacturers were not at risk of losing production orders for an engine designed under the competitive bidding regime.

Both military and airframe manufacturers were aware that using competitive bidding for production orders was impeding technological progress in the first half of the 1920s. Pressure from both parties led to the inclusion of changes in the procurement procedures in Section 10 of the Air Corps Act of 1926, which established the Air Corps as a wing of the Army and provided for a five-year expansion in military aircraft purchases. While Congress continued to insist on competitive bidding, the language of the 1926 Act included a loophole that Air Corps and Navy procurement officers exploited to avoid competitive bidding in favor of contracts negotiated with individual manufacturers. As a result, from 1926 to 1934 the air arm made $38 million in purchases using negotiated contracts and just $750,000 under competitive bidding (Holley, 1964, p. 117). This represented a substantial regime change in airframe procurement: from competitive bidding to negotiated fixed-price production contracts with the firm that produced the design.

To understand how these changes affected aircraft and engine manufacturers it is useful to have some understanding of procurement policies during this period, which were very different from today. Most new designs were produced by aircraft manufacturers at their own expense in the hope the military would choose to adopt their new aircraft.[10] These "private ventures" were sometimes based on government specifications, while in other cases aircraft companies simply aimed to produce a substantially better plane than the one currently in use.[11] Other new designs were produced as collaborations between manufacturers

[9]Pratt & Whitney had been founded in 1925 by former Wright employees with the encouragement of the Navy. This occurred in part as a response to Wright's purchase of another engine producer Lawrence, as well as the concurrent decline of interest in aero-engine production by Packard, which left the military concerned about becoming overly-reliant on Wright. This led the military to encourage the emergence of Pratt & Whitney in order to maintain some balance in the market.

[10]See data and discussion in Appendix D.

[11]For example, in 1930 Boeing produced a new bomber design (YB-9), the first all-metal monoplane bomber, as a private venture based on the lessons learned from the Model 200 Monomail. In response, the Glenn L. Martin Company produced their own private venture, the Martin Model 123 which would become

and the military. Once a prototype was ready, a few versions would be delivered to the military for testing and evaluation. If a design proved satisfactory then the design would be recommended to the Procurement Board of each branch. Working with an essentially fixed budget each year, procurement boards would make a preliminary decision about how many planes, engines, and other pieces of equipment to purchase based on estimated costs. As actual cost figures were agreed upon, either through competitive bidding (before 1926) or direct negotiation, purchase numbers would be modified to stay within the budget, or certain items could be cancelled or purchases delayed to future years. This meant higher prices for certain aircraft would have to be compensated for either by reducing quantity of that type, or by cancelling other purchases.[12] Purchase prices for equipment were fixed (though regularly adjusted as the military asked for modifications of the original design), unlike the cost-plus or other contracts that are commonly used today. The demand system used in our model is intended to reflect these features in a stylized way.

Congress passed other legislation affecting the aircraft industry in the middle of the 1920s. The Air Mail Act of 1925 (Kelly Act) authorized the Post Office to contract with private air carriers for the carriage of mail, effectively launching the commercial aviation industry. The Air Commerce Act of 1926 empowered the Department of Commerce to regulate and promote air commerce, including licensing pilots and aircraft, developing air routes and airfields, and collecting statistics.

These were important changes for civil aviation and, because of their timing, they present a potential concern for our study. However, several features of the aircraft industry suggest that the changes initiated by these laws are not likely to be behind our findings. One factor is simply the sheer size of military procurement relative to civil aircraft purchases. From 1926 to 1936, military aircraft purchases totaled $88 million while civil aircraft purchases were worth approximately $55 million (Koistinen, 1998).[13] Military procurement was particularly important for high-performance aircraft, a critical feature for our study since these are the main focus of our analysis. In terms of unit value, military purchases of both airframes and engines were much more expensive than civil sales, reflecting "the exceptionally rigorous performance and quality requirements" of military aircraft, while most civilian aircraft purchases "consisted of single-engine, small planes that were relatively inexpensive to produce"

the B-10 bomber. The Boeing Model 66 (XP-8) pursuit aircraft of 1926 was another example of a private venture design.

[12]See Appendix B.3 for further discussion.

[13]Data collected from the *Aircraft Yearbooks* published by the Aircraft Chamber of Commerce and generously provided to us by Paul Rhode provides somewhat different figures which indicate military purchases from 1925-1935 of 113$ million and civilian purchases of $109 million. The discrepancy between these figures and those provided by Koistinen (1998) is most likely due to the specific equipment included as part of the purchase. Export sales were also important for some companies, but prior to the mid-1930s the vast majority of these sales were in older military aircraft designs. For defense purposes manufacturers were banned from exporting new designs until two years after they were introduced. This delay meant that export sales were likely to have little impact on the innovation decisions that we study.

Koistinen (1998, p. 191).[14] The military also purchased much more expensive engines than the civilian market. For example, data from Holley (1964, p. 20) shows that the average unit value of military engines purchased in 1928 was $4,736 while the average for civilian engines was just $1,551. In 1932 the corresponding figures were $5,872 for the military and $3,565 for the civil market. Similar patterns appear if we focus on engine power: Holley (1964, pp. 20–21) reports that in 1937, 2,289 engines were purchased for civil aircraft, but only 88 produced over 600 horsepower and 1,393 were under 50 horsepower. Military purchases amounted to 1,800 engines, of which 1,276 were over 700 horsepower, and none below 50.

The military's demand for frontier designs also increased the speed of product turnover and the need for R&D. Holley (1964, p. 21) writes that,

> *. . . the necessity of turning out aircraft of progressively superior performance to meet the tactically competitive requirements of the military market involved the annual investment of large sums for research and development in contrast to the civil aircraft market, where a single basic design occasionally continued to amortize initial development costs over a period of several years.*

Contemporary sources also highlight the role military orders played in innovation during the 1920s. For example, Rae (1968, p. 17) describes how the aircraft manufacturer Grover Loening, "complained that lack of government orders might compel him to stop commercial work, and he pointed out a feature of the aircraft business that would in time be recognized as fundamental: no private company could bear the cost of development work on commercial planes unless it had support from government contracts." Given these features, it is unlikely that changes in the civilian market substantially influenced the high-performance end of the market that we focus on, at least before the entry of the DC-3 in 1935, which marked a turning point in civilian aviation.[15]

Consistent with the argument that military demand played a central role in aircraft innovation in the 1920s and 1930s is the fact that the two companies that would lead American commercial aviation into the modern era in the mid-1930s, Douglas and Boeing, were primarily focused on military production.[16] The fact that these firms drove innovation in the mid-1930s, rather than firms more focused on the civilian market (e.g., Lockheed and Fairchild), highlights the central role of the military market in driving civilian innovation after 1927. Later, we discuss in detail the sequence of designs that led to these breakthroughs.

[14] See figure in Appendix B.2.

[15] Even after this point, however, there is evidence that military contracts played an important role in driving innovation in civil aviation, particularly in the years just after World War II (Jaworski and Smyth, 2016).

[16] Boeing (as part of United Aircraft), which produced the first modern commercial passenger plane, the Model 247 of 1933, made two-thirds of its sales to the government between 1927 and 1933. Moreover, as we discuss below, the Model 247 was produced as a direct result of an earlier bomber design. For Douglas, which would produce the even more important DC-3 in 1935, government sales accounted for over 90% of revenues during the same period (Rae, 1968, p. 43).

The US government was also active in research in airframes, engines, and components. Most of this research took place under the aegis of the National Advisory Committee on Aeronautics (NACA), the predecessor of NASA. NACA was involved in research on a wide variety of topics and published a number of technical reports each year with their results. While the NACA budget grew across the study period, there was no break in the pace of growth around 1926 that would threaten our identification strategy (see Appendix Figure B2). Morevoer, NACA's reports were publicly available and would have been disseminated to foreign manufacturers by their governments, just as the US government was active in disseminating the reports emanating from foreign research agencies to US firms. NACA had a particularly close relationship with its British counterpart, the British Aeronautical Research Committee.[17] Similar government-funded research organizations existed in each comparison country. Because of the wide dissemination of public aeronautical research, and the spread of this research across countries, comparing innovation patterns across countries helps to control for potential technological breakthroughs that affect all countries.

In Appendix B we provide additional background information on the state of the aircraft industry in our comparison countries. For airframes, we compare patterns in the United States to those in the United Kingdom and Japan. For engines, we compare the United States with the United Kingdom, Germany, and Italy. For both airframes and engines we pay particular attention to patterns in the United Kingdom, which was the most comparable to the United States during this period. Other comparison countries were considered but were not used for various reasons.[18]

Finally, note that our study spans a period of enormous volatility in the broader economy, from the roaring twenties into the Great Depression. It is notable that the aircraft industry fared better during the early 1930s than other sectors of the economy. Patillo (1998) describes the period from 1927 to 1935 as a "golden age" for the industry. A surge in interest in aviation came after Charles Lindbergh's flight across the Atlantic in May 1927 and was followed by a number of other record flights (Patillo, 1998, p. 65). This boom gave a boost to nascent airlines, attracted attention from Wall Street, and led several aircraft manufacturers to go public (e.g., Douglas in 1928 and Consolidated in 1929).

3 Theory

This section presents a simple theory describing how granting IP protection to one group of producers impacts innovation rates among those producers as well as for producers of a key complementary good. The mechanism in the model is general and can potentially be

[17]See, e.g., discussion in National Advisory Committee for Aeronautics (1923, pp. 53-54)

[18]For example, France is not included as a comparison country because in 1928 the French government introduced a "prototype policy" aimed at spurring the introduction of new aircraft prototypes. Since this corresponds fairly closely to the timing of the policy change in the United States that we study, France will not provide a clean comparison for our main analysis. Instead, in Appendix G we provide a separate analysis of the prototype policy. These results provide validation for our basic approach.

applied in any setting where the strength of IP protection changes for one out of a set of complementary or substitute goods. However, we tailor the details of our model to fit the aircraft industry. As we discuss later, alternative models may explain some of the patterns observed in our empirical analysis. Therefore, we also use the model to derive additional predictions that can be taken to the data.

The model is partial equilibrium to match our focus on a single industry. We consider a static one-period problem in which firms choose the level of investment in innovation for new designs. Firms observe the outcome of the innovation process and then produce, after which markets clear.

3.1 Demand

The government, the sole source of demand, purchases aircraft in a number of product categories (e.g., fighters, bombers) indexed by m. Each aircraft is composed of two components, airframes and engines, indexed by $j \in \{A, E\}$. Initially, firms produce only one of these products. To keep things simple, we suppose that each product market requires a different type of airframe and engine. We abstract from the possibility that different aircraft use a different number of engines and just consider a single composite "engine good" within each market, so each aircraft requires one airframe unit and one engine unit. Let P_{mA} be the price of the airframe of type m and P_{mE} be the price of the engine unit of type m. Thus, the cost to the government of an aircraft of type m is $P_m = P_{mA} + P_{mE}$.

There is variation in the quality of the product that a firm i of type j can produce in sector m. Within each product type m and input type j there is one leading firm, denoted by L, that has the ability to produce the highest quality product, which we call the frontier technology. All other firms, which can only produce products that are considered obsolete, are followers (denoted by F) in that market and input type. The government is only interested in purchasing the frontier technology in a particularly product and input type.[19] This reflects the empirical setting, where the military typically only purchased the best design available for a particularly aircraft type in a particular time period.[20]

The military's value (in dollars) from purchasing a quantity x of the frontier aircraft of a particular type given an overall budget constraint A is given by:

$$V(x_m, P_{mA}, P_{mE}) = \lambda x_m^\rho + [A - x_m(P_{mA} + P_{mE})]$$

[19]Note that this is similar to a limit case in a model such as Aghion et al. (2005) with no competition between leader and follower firms.

[20]The idea that the military only wanted to purchase the best available aircraft of each type is generally consistent with description of procurement offered in Holley (1964, p. 76) . However, he notes that there were some exceptions. In particular, because Congress tended to judge the strength of the air wing based on the number of planes, there was some pressure to continue buying older and cheaper versions in order to hit the acquisition numbers that Congress expected. However, the military tried to avoid this whenever possible.

where $\rho \in (0,1)$. The budget constraint A is meant to reflect the appropriation process, in which Congress set aside a specific amount of funds for military use over a particular period of time.[21] This expression incorporates a diminishing value of aircraft as the quantity of aircraft of that type increases as well as a constant value of remaining funds which can be allocated to other purposes. Given an agreed-upon set of prices, the government will choose x_m to maximize the value above. This yields,

$$x_m = (P_{mA} + P_{me})^{\frac{1}{\rho-1}} (\rho\lambda)^{\frac{1}{1-\rho}} \tag{1}$$

Note that the quantity that the military is willing to purchase is falling in the price it must pay for the combination of airframes and engines.

It is worth pausing to highlight important features of the proposed demand system. First, we assume strong (Leontief) complementarity in the *quantity* of engines and airframes consumed. This is a natural reflection of the industry that we study. However, in a more general model the degree of complementarity or substitutability between goods will be important for the results.[22] Second, there is no complementarity or substitutability between the *quality* of airframes and engines in sector m. Making this assumption allows us to focus attention on the way that changes in market power caused by the introduction of IP protection affects innovation. If instead we allow for complementarity or substitutability in quality, how we model that interaction within the black box of the production function would end up driving the results obtained from the model. As we discuss below, it is not implausible that such effects existed in the empirical setting, and so we will confront them in the empirical portion of the analysis. Introducing these interactions into the theory, however, would only serve to obscure the key forces that our model is meant to illustrate.

3.2 Supply

In our baseline model there are N_E engine firms and N_A producers of airframes. At the beginning of the period there is one incumbent leading firm which has access to the best existing design.[23] All firms then make decisions about how much to invest in innovation in each market segment m. The innovation investment of some firm i of type j is given by I_{mji}. Given this investment, the firm innovates with probability $\phi(I_{mji})$, where $\phi(\cdot)$ is assumed to be a continuously differentiable function satisfying $\phi(0) = 0$, $\phi'(I_{mji}) > 0$, $\phi''(I_{mji}) < 0$, $\lim_{I_{mji}\to\infty} \phi(I_{mji}) = 1$, and $\lim_{I_{mji}\to 0} \phi'(I_{mji}) \to +\infty$.

The initial leading technology is observable by all market participants, a feature moti-

[21] Appendix B.3 provides a description of this process drawing on records of the Army Air Corps Procurement Planning Board obtained from the U.S. Archives. These records make it clear that military procurement authorities faced constraints consistent with our assumptions.

[22] Lerner and Tirole (2004) show this for the case of patent pools.

[23] The reason we have an incumbent leader in the model is to ensure that, when IP protection is available, there is an incumbent firm that sell products (and extract rents) from the leading design even if no firm successfully innovates.

vated by our empirical setting, so any new innovation represents an improvement over the current leading design rather than the best previous design of the innovating firm. Once innovation outcomes are realized there are three possible scenarios. If no firm successfully innovates in market segment m, then the initial technology leader in that segment remains the leader. If only one firm innovates, then that firm is the new technology leader. If multiple firms successfully innovate, then each firm has an equal probability that its innovation is superior, in which case it becomes the market leader.

To keep things simple, production costs are modeled as $TC_{mji} = \gamma_j x_{mji}$ where x_{mji} is firm output and γ_j can be different for engine and airframe makers. We have also explored alternative production cost structures incorporating fixed costs as well as falling marginal costs reflecting learning-by-doing.[24] These do not substantially change the key forces at work in the model, so we have opted for the simpler approach in our main analysis.

Firms make profits from two sources. Total profit π_{mj} is the sum of profits from producing and selling products $\tilde{\pi}_{mj}$ plus a fixed fee G paid to a firm if it produces the leading design in a product type and category.

3.3 Solving the Model

We solve the model under two alternative market structures. In the first, airframe manufacturers do not have property rights over their designs and instead compete for production orders on price. In the second, airframe firms that produce a new frontier design have property rights over that design. In both cases engine makers have property rights over the production of a design that they create. Comparing the outcomes in these two settings reveals the impact of a policy change that provides IP rights to airframe producers, such as the one featured in our empirical analysis. In this context, the empirical experiment that we study can be thought of as a decision by the government to pre-commit to one of these two market structures.

When manufacturers of a particular good do not have property rights over their new designs, designs are put up for competitive bidding based on price. We therefore model this market as Bertrand competition. If manufacturers do have property rights of their designs, we treat the firm with the best design as a monopolist. This monopolist firm the engages in direct bartaining with the monopsonist government purchaser. Naturally, these different market structures will have different implications for the profits of firms of type j within each market segment m. To solve the model, we begin by taking π_{mj} as given and deriving equilibrium innovation investment decisions. We then solve for profit levels under alternative market structures.

[24]For a discussion of learning in airframe production see Asher (1956) and, more recently, Benkard (2000).

3.4 Innovation Decisions

We denote the innovation investment of the market leader I_{mjL} and the investment of the follower firms as I_{mjF}. Note that all of the follower firms face a symmetric choice so they will all make the same innovation investment decision. The expected payoff of innovation for the market leader is,

$$\begin{aligned} \Lambda_L(I_{mjL}) &= \pi_{mj}[1-\phi(I_{mjF})]^{N-1} \\ &+ \phi(I_{mjL})\pi_{mj}\sum_{n=1}^{N-1}\left(\frac{1}{n+1}\right)\binom{N-1}{n}\phi(I_{mjF})^n[1-\phi(I_{mjF})]^{N-n-1} \\ &- I_{mjL}\,. \end{aligned} \tag{2}$$

The top row on the right-hand side of this expression reflects the return if no other firm innovates, in which case the market leader retains leadership regardless of whether or not it successfully innovates. The second row is the expected payoff if the leader innovates but other firms do so as well. In this case the chance that the current leader's innovation is chosen for production by the government is $1/(n+1)$ where $n+1$ is the total number of innovating firms. The last term reflects the cost of innovation.

The expected payoff for a follower firm F' given investment $I_{mF'}$ is,

$$\begin{aligned} \Lambda_{F'}(I_{mjF'}) &= \phi(I_{mkF'})\pi_{mj}\left[\sum_{n=0}^{N-2}\left(\frac{1-\phi(I_{mjL})}{n+1}+\frac{\phi(I_{mjL})}{n+2}\right)\right. \\ &\left.\binom{N-2}{n}\phi(I_{mjF})^n[1-\phi(I_{mjF})]^{N-n-2}\right] - I_{mjF'} \end{aligned} \tag{3}$$

Taking first order conditions, the leader sets I_{mjL} such that,

$$\phi'(I_{mjL}) = \left[\pi_{mj}\sum_{n=1}^{N-1}\left(\frac{1}{n+1}\right)\binom{N-1}{n}\phi(I_{mjF})^n[1-\phi(I_{mjF})]^{N-n-1}\right]^{-1} \tag{4}$$

The follower F' sets $I_{mjF'}$ such that,

$$\phi'(I_{mjF'}) = \left[\pi_{mj}\sum_{n=0}^{N-2}\left(\frac{1-\phi(I_{mjL})}{n+1}+\frac{\phi(I_{mjL})}{n+2}\right)\binom{N-2}{n}\phi(I_{mjF})^n[1-\phi(I_{mjF})]^{N-n-2}\right]^{-1} \tag{5}$$

Note that, given the assumption that $\phi''(\cdot) < 0$, the two expressions above constitute optimal solutions to the leader's and the follower's problems taking as given the investments of all other firms.

In equilibrium it must be the case that $I_{mjF'} = I_{mjF}$ for all follower firms. Proving equilibrium existence therefore involves showing that equations (4) and (5) can be satisfied under this condition.

Proposition 1: Taking π_{mj} as given, there is a unique equilibrium innovation investment decision $I_{mjF}*$ for follower firms and a unique equilibrium investment decision $I_{mjL}*$ for the initial leader firm in each sector m and product type j.

Proof: See Appendix A.1.

Proposition 2: Equilibrium innovation investments for both leader and follower firms of type j in sector m are strictly increasing in π_{mj}.

Proof: See Appendix A.1.1.

Corollary 1: When $\pi_{mj} > 0$, $I_{mji}* > 0$ for all i firms of type j within sector m.

This follows directly from equations (2) and (3) together with the assumptions on $\phi(\cdot)$ and implies that as long as there is a fixed fee offered for new leading designs, there will be always be some innovation investment, even when profits from production are zero.[25]

3.5 Profits with IP protection in airframes

When both airframe and engine suppliers have IP protection, the government negotiates prices with the leading producers in each sector. We model this monpolist-monopsonist interaction as Nash-in-Nash price bargaining, following Horn and Wolinsky (1988) and Collard-Wexler, Gowrisankaran and Lee (2019), in which bargaining over the price of one input takes place taking as given the price of the other. If the government comes to an agreement with both suppliers then the government's surplus is $V(x_m, P_{mA}, P_{mE})$. Without an agreement the government spends no money on aircraft of type m and obtains surplus $V(0,0,0) = A$. For airframe producers, the surplus obtained from an agreement (production profit) is given by,

$$\tilde{\pi}_{mA} = x_m(P_{mA} - \gamma_A)$$

and a similar expression holds for engine makers. If no agreement is reached between the suppliers and the government then each supplier obtains zero profit.

Under Nash-in-Nash bargaining, the airframe price is given by,

$$P_{mA} = \arg\max_{P_{ma}} \quad [\lambda x_m^{\rho} + A - x_m(P_{mA} + P_{mE}) - A]\,[x_m(P_{mA} - \gamma_A)]$$

[25] It is worth noting that follower firms will make larger investments in innovation (Arrow's replacement effect). This is because a follower firm benefits from innovating when no other firm innovates. The leader does not, since when no other firm innovates it remains the leader regardless of whether it innovates. This gives the follower firms somewhat greater innovation incentives than the leader.

taking as given that the government reaches an agreement with the engine maker with negotiated price P_{mE}. Substituting in for x_m using Eq. 1 and rearranging we obtain,

$$P_{mA} = \arg\max_{P_{mA}} \quad C\left(P_{mA} + P_{mE}\right)^{\frac{\rho+1}{\rho-1}} (\rho\lambda)^{\frac{1}{1-\rho}} (P_{mA} - \gamma_a)$$

where, $C = \left[\lambda^{\frac{2}{1-\rho}} \rho^{\frac{\rho+1}{1-\rho}} - \lambda^{\frac{2}{1-\rho}} \rho^{\frac{2}{1-\rho}}\right] > 0$.

The first order condition for this maximization yields,

$$P_{mA} - \gamma_a = (P_{mA} + P_{mE}) \left(\frac{1-\rho}{1+\rho}\right).$$

A similar expression holds for the price of engines. These expressions implicitly define the equilibrium prices negotiated between the government and each type of supplier. Simplifying, we have,

$$P_{mA} = \frac{\gamma_a(1+\rho) + P_{mE}(1-\rho)}{2\rho} \quad \text{and} \quad P_{mE} = \frac{\gamma_e(1+\rho) + P_{mA}(1-\rho)}{2\rho}$$

Note that these expressions can be used to show that the difference between the prices of engines and airframes is driven entirely by differences in the underlying costs, i.e., $P_{mA} = P_{mE} + (\gamma_a - \gamma_e)$.

Solving these expressions, we obtain,

$$P_{mA} = \frac{\gamma_a 2\rho + \gamma_e(1-\rho)}{3\rho - 1}$$

and a corresponding expression for P_{mE}. We can see from this expression that to obtain a positive finite price we need $\rho > 1/3$. Henceforth we assume that this condition is satisfied. The total price for an aircraft under these conditions is then,

$$P_m = P_{mA} + P_{mE} = \frac{(\gamma_a + \gamma_e)(1+\rho)}{3\rho - 1}$$

Given these prices, the production profit for the engine producer when the airframe producer has access to IP protection is given by,

$$\tilde{\pi}^{IP}_{mE} = (\gamma_a + \gamma_e)^{\frac{\rho}{\rho-1}} (1+\rho)^{\frac{1}{\rho-1}} (3\rho - 1)^{\frac{\rho}{1-\rho}} (\rho\gamma)^{\frac{1}{1-\rho}} (1-\rho) \tag{6}$$

A similar expression holds for the airframe producer.

3.6 Profits without IP protection in airframes

With no IP protection in airframes, the government is free to have any airframe firm produce its favored design. Thus, airframe producing firms compete on price, which is bid down to the marginal cost: $P_{mA} = \gamma_A$. Production profits are $\tilde{\pi}_{mA} = 0$ and total profits for the firm that produced the leading design are $\pi_{mA} = G$.

The leading Engine producer then engages in monpoloist-monopsonist bargaining with the government taking as given $P_{mA} = \gamma_A$. Under these circumastances, the negotiated price for engines is given by:

$$P_{mE} = \frac{\gamma_e(1+\rho) + \gamma_a(1-\rho)}{2\rho}$$

and the "NO IP" production profit for the engine maker is,

$$\tilde{\pi}^{NOIP}_{mE} = (\gamma_e + \gamma_a)^{\frac{\rho}{\rho-1}}(1+\rho)^{\frac{1}{\rho-1}}(1-\rho)(\rho\lambda)^{\frac{1}{1-\rho}}(2\rho)^{\frac{\rho}{1-\rho}} \tag{7}$$

This leads us to the following proposition:

Proposition 3: In the absence of merger activity, granting IP protection to airframe producers increases innovation in airframes and decrease innovation in engines.

Proof: From Prop. 2 we know that innovation investments are increasing in profits. Taking the ratio of the production profits given in equation (6) to those from equation (7), we have

$$\frac{\tilde{\pi}^{IP}_{mE}}{\tilde{\pi}^{NOIP}_{mE}} = \left(\frac{3\rho - 1}{2\rho}\right)^{\frac{\rho}{1-\rho}} \quad < \quad 1 \qquad \text{for} \qquad \rho \in (1/3, 1)\,,$$

which tells us that overall profits for engine makers are lower when airframe producers have access to IP protection.

3.7 Additional Theoretical Predictions

Next, we look for additional predictions that emerge from the theory and can be taken to the data. Specifically, we focus on the implications of the model for the incentives for firms to undertake what we will call "vertical-complement" mergers, i.e., mergers between airframe and engine producers.

Initially, when airframe producers did not have access to IP protection, in order to obtain an order for airframes the firm must charge a price no greater than the marginal cost of the other airframe producers. Given this, even if an airframe producer has merged with an engine maker, the airframe division will be forced to set price equal to marginal cost and the payoffs for the combined firm will be the same as the payoffs of the two separate firms. Thus, without IP protection there is no incentive for airframe and engine producers to merge.

However, consider the incentives for vertical-complement mergers once IP protection is available in the airframe sector. If the leading engine and airframe producers merge, then the merged firm will engage in joint bargaining with the government over the total aircraft price P_m. The Nash bargaining price is given by,

$$P_m = \arg\max_{P_m} \left[\lambda x_m^{\rho} + A - P_m x_m - A\right]\left[x_m(P_m - \gamma_a - \gamma_e)\right]$$

Solving, this yields the following production profit for the merged firm,

$$\tilde{\pi}^{MERGED} = (\gamma_a + \gamma_e)^{\frac{\rho}{\rho-1}} (1+\rho)^{\frac{1}{\rho-1}} (2\rho)^{\frac{\rho}{1-\rho}} (\rho\lambda)^{\frac{1}{1-\rho}} (1-\rho)\,.$$

This leads us to the following proposition.

Proposition 4: The introduction of IP protection in the airframe industry generates incentives for mergers between airframe and engine producers for values of $\rho \in (1/3, 1/2)$.

Proof: Taking the ratio of the production profits obtained when the firms remain independent to the profits obtained when the firms merge, we have:

$$\frac{2\,\pi^{IP}}{\pi^{MERGED}} = 2\left(\frac{3\rho - 1}{2\rho}\right)^{\frac{\rho}{1-\rho}}$$

which is less than 1 for $\rho \in (1/3, 1/2)$.

This shows that under certain circumstances the model predicts that granting IP protection will lead firms to undertake vertical-complement mergers. Note that, because this model does not predict that mergers will take place under all circumstances, the lack of merger activity cannot be used to reject the model (unless ρ can be directly estimated, which is not possible in our setting). However, if we do observe firms undertaking vertical-complement mergers, that activity can be explained by the theory.

Additionally, the model makes predictions about which airframe and engine producers we would expect to merge. Specifically, the benefits of merging depend on the airframe producer and engine producer being leaders in the same market. Thus, we expect engine makers to merge with larger airframe producers with leadership positions in more of the markets in which the engine maker is also the leader. Moreover, once an engine and airframe producer have merged, we expect them to focus their innovation investments in the same aircraft types.

4 Data and Variables

The main data used in the empirical analysis are drawn from detailed descriptions of aircraft designs and are available due in large part to the high level of general interest in aircraft–particularly military aircraft. These data were compiled from several books describing airframe and aircraft engine designs. The data include the near-universe of important military airframe and aero-engine designs produced between 1916 and 1938 in the United States and several comparison countries. In Appendix C, we provide further detail on these sources.

The aircraft in our data are divided into various categories (e.g., fighters), which are referred to as types or market segments in the theory. In the empirical analysis we focus primarily on fighters for two reasons. First, fighters were the most likely to see combat with other aircraft and, therefore, this market segment demanded high-performance characteristics. Since the measures we use to track innovation reflect high-performance (rather than low costs), fighters are a natural focus for our analysis. Second, fighters were the most distinct from civilian designs.[26] In robustness exercises we also consider other aircraft categories such as bombers or reconnaissance planes.

Within each aircraft category we observe the introduction of completely new aircraft designs (e.g., Boeing's PW-9 fighter family) as well as new models of a particular design with different performance characteristics (e.g., the PW-9A and PW-9B versions of the PW-9 fighter). An observation in our airframe data is the introduction of a new model, including new versions of existing designs. For each model we typically observe the year of first delivery, producer, a variety of physical and performance characteristics, and the number of airframes delivered.[27]

Our preferred measure of airframes performance is wing load, calculated as gross weight divided by wing area. This is a standard performance measure in the aircraft industry that reflects improvements through increasing lift and reducing drag.[28] In addition, we also present results using alternative measures of airframe performance as robustness. Performance characteristics such as maximum speed, cruising speed, take-off climb rate, distance range, and altitude ceiling are reported for a subset of the designs covered by our data. In general, these aspects of performance are highly correlated with wing load (see Appendix Figure E1).

To measure performance of aircraft engines we use horsepower produced per unit of engine

[26]There are no examples of the same model of aircraft being used by the military as a fighter and also sold for civil uses in substantial numbers. However, as discussed below, other designs, particularly bombers, did act as an important starting point for the development of new commercial designs.

[27]There is some question in our data about the timing of the introduction of new aircraft or engine models. This is because there is a lag between the timing of, say, the first flight of a new model and when the first version is delivered. Similarly, in engines there is a lag between when an engine is first run and when the production version is ready. In our airframe data, new models are typically assigned the year in which the first version was delivered. For engines, in our main data the year assigned to a new engine model is typically the first year in which that model was purchased by the military. One exception to these rules is that when the data is from Jane's, the year of introduction is the first year that the engine appears in Jane's.

[28]Phillips (1971) writes that, "Wing loading...is without question a direct measure of very important changes in airfoil technology. It probably is also an indirect or proxy indicator of parallel changes in the technology of other aspects of the airframe."

displacement. This provides a direct measure of progress in engine technology. Higher engine piston displacement indicates that an engine is larger and heavier. An engine that generates more horsepower for the same displacement volume indicates a better technology. Our data also identify whether an engine was air-cooled versus liquid-cooled. This is an important distinction which we control for in our regression analysis. We also report results using horsepower divided by engine weight (in pounds) in the appendix. This measure is highly correlated with horsepower per unit of engine displacement for the United States (0.67) and United Kingdom (0.61). However, we prefer to use horsepower per engine displacement in our main results because displacement is straightforward to measure, whereas the measurement of engine weight can vary substantially depending on whether auxiliary equipment (starters, turbochargers, superchargers, etc.) are included in the engine weight.

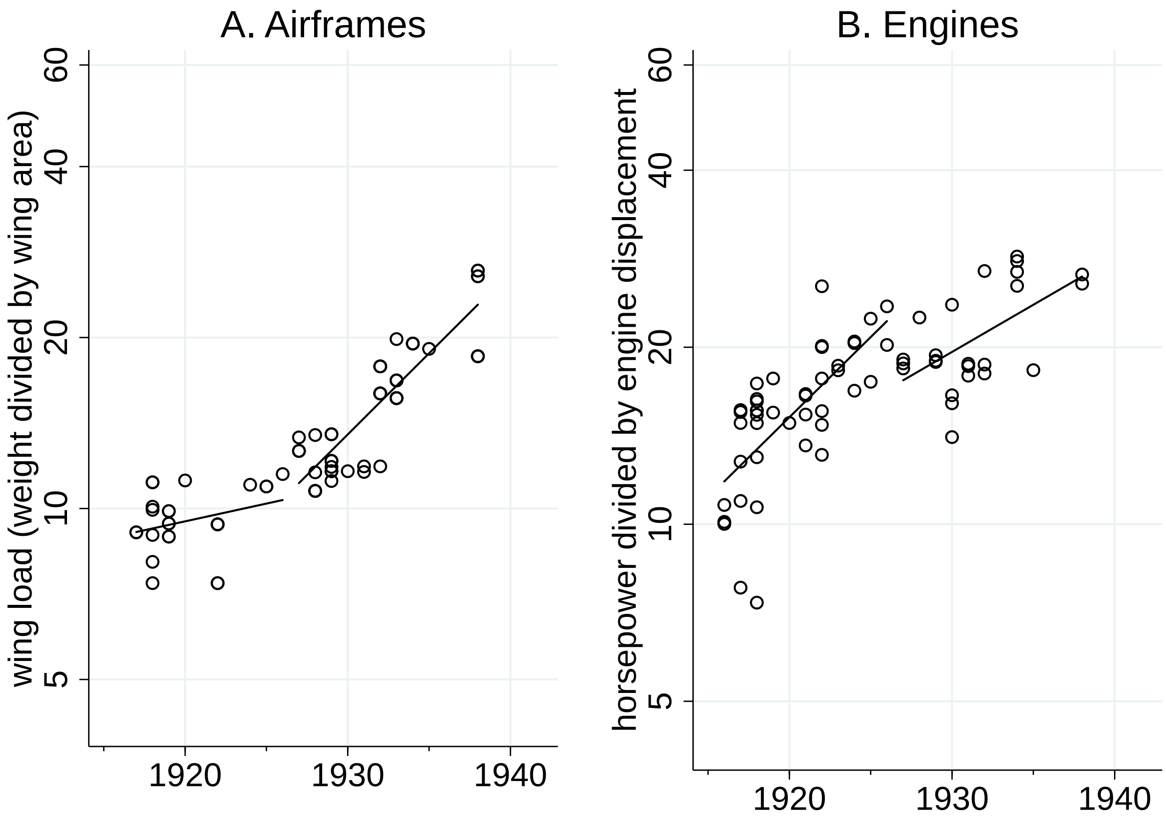
It is worth noting that we focus our analysis on performance characteristics rather than the number of designs produced. There are several reasons for this. One is that obtaining one design with excellent performance, rather than many mediocre designs, was the objective of the military. The number of designs produced is also endogenous to the performance of the current leading design; firms may be reluctant to invest in new designs if the current design has excellent performance.

Ideally, we would like to have data on firm profits, which play an important role in our proposed mechanism. Unfortunately, such data are not available before the late 1920s. Even when profit data start being reported, they are effectively useless for our purposes. For example, Vander Meulen (1991, p. 43) warns, "Profitability data remains scarce until most aircraft firms went public in the late 1920s. Even then it is difficult to use because of the standard practice of deferring large development charges against future earnings on expected production contracts that usually did not materialize." For these reasons, we focus on airframe and aero-engine performance characteristics in our empirical analysis.

5 Results

In this section we present our main results looking at the effect of the 1926 change in IP protection on innovation in the aircraft industry, including both airframe and aero-engine producers. In the context of the model, this policy change should be viewed as the military buyer shifting from a pre-1926 regime in which it had pre-committed to purchasing airframes through open, competitive bidding, to a new post-1926 regime in which the military committed to identifying the best available design and then conducting bilateral bargaining with the designing firm over the purchase price of each aircraft (with engines obtained through bilateral bargaining in both regimes). Our analysis of airframes focuses on fighters, though in the appendix we discuss the results for other market segments (e.g., bombers and reconnaissance) as well as civilian purchases.

Figure 1: Airframe and Aero-Engine Innovation in the United States



Notes: The figure shows innovation in military fighter airframes and aero engines for the Untied States between 1915 and 1938. Each dot plots gross weight divided by total wing area–i.e., wing load–of each fighter airframe (Panel A) and horspower divided by engine displacement for each aero-engine (Panel B) introduced in a given year. The solid black lines in each panel reflect the best fit before and after 1926.

5.1 Airframes

As a starting point, Figure 1A provides graphical evidence for technological progress in fighter airframe performance in the United States over time. Technological progress measured using wing load was slow before 1926 and increased dramatically afterward. Thus, focusing only on changes in the United States over time, granting IP protection for new designs was accompanied by an acceleration in airframe innovation. The timing of the acceleration fits what we know about the length of time needed to develop new designs reasonably well. In Appendix D we present some data suggesting that it typically took between one and two years to produce a new original airframe design. Each new model was rooted in existing designs, so even with this relatively short development period we might expect that it would take one or two product cycles before the effect of increased innovative effort becomes substantial. This timing seems consistent with the patterns in Figure 1A, where we see some evidence of progress in the late 1920s and then much more notable gains in the early and mid-1930s.

To quantify the patterns shown in Figure 1A, we begin with a simple specification that exploits only variation over time in the United States. Specifically, we estimate the following regression,

$$\begin{aligned} \ln Y_{dt} = {} & \alpha_{\text{before}} \mathbf{1}\{\text{Before 1926}\}_t \times \text{year}_t \\ & + \alpha_{\text{after}} \mathbf{1}\{\text{After 1926}\}_t \times \text{year}_t + \delta X_{dt} + \varepsilon_{dt} \end{aligned} \tag{8}$$

where the dependent variable, Y_{dt}, is wing load for airframe design d in year t. The coefficients of interest quantify the rate of technological progress in the United States before (α_{before}) and after (α_{after}) 1926. X_{dt} includes the constant term and a dummy variable equal to one for observations after 1926 to control for differences in the level of innovation before and after the change in intellectual property protection. Note that since an observation in our data is the introduction of a new aircraft model there may be multiple observations in each year. Standard errors are clustered by year. One might worry about serial correlation in these regression. However, such concerns are testable and an examination of the residuals reveals evidence of correlated errors for observations within the same year but little evidence of serial correlation across years.[29] Thus, serial correlation does not appear to be an important feature of the data we study.

The results for estimating equation (8) are presented in the first two columns of Table 1. The estimated pre- versus post-1926 trend in innovation for the United States is shown either weighted by the number purchased (column 1) or unweighted (column 2). Improvements in fighter wing load were between 0.1 and 1.4 percent before 1926 compared with 7.9 and 6.6 percent per year after 1926. Below the estimated coefficients we report the F-statistic and

[29] To formally test for the correlation over time we collapse our data to the country-level and calculate the test statistic under the null hypothesis of no serial correlation of the residuals from the first-differenced regression that includes country fixed effects (see Wooldridge, 2002; Drukker, 2003). The p-value obtained from this exercise for our main fighter data is 0.1975.

p-value for the equality of the coefficients, which confirms that in both cases we can reject the null hypothesis of equality. This suggests that increased innovation in airframes followed greater IP protection.

The results so far are consistent with increased technological progress following the 1926 policy change that provided greater IP protection. An important concern in this context is that technological progress attributed to IP protection is in fact due to unobserved factors the led to improvements in airframe design regardless of changes in the IP regime in the United States. This would be the case if there was a breakthrough that was widely known and adopted across countries. For example, if there were information sharing across government research organizations or highly publicized improvements by industry participants. To examine whether worldwide changes in the technological frontier can explain increased innovation we pool data for the United States, United Kingdom, and Japan.[30] Specifically, we estimate,

$$\begin{aligned} \ln Y_{dt} = {} & \beta_{\text{before}} \mathbf{1}\{\text{Before 1926}\}_t \times \text{year}_t \times \text{US}_d \\ & + \beta_{\text{after}} \mathbf{1}\{\text{After 1926}\}_t \times \text{year}_t \times \text{US}_d + \gamma X_{dt} + \nu_{dt} \end{aligned} \tag{9}$$

where the coefficients β_{before} and β_{after}, respectively, measure the rate of innovation in the United States relative to other countries before and after 1926. In addition, X_{dt} includes controls either innovation trends in each country before and after 1926 or a full set of time fixed effects, so that β_{before} and β_{after} measure innovation in the United States relative to other countries. Standard errors are clustered by country-year.[31]

The remaining columns of Table 1 show the results from estimating versions of equation (9) with the log of wing load as the dependent variable. Columns 3 and 4 compare the United States to the United Kingdom and Japan with and without weighting by the number purchased, respectively. Column 5 adds year fixed effects, column 6 controls for the number of engines and engine horsepower, and column 7 includes both year fixed effects and the engine controls. The results show that technological progress in the United States was slower before 1926 relative to other countries and accelerated after 1926; the reported F-statistics (and p-values) confirm that we can reject the null hypothesis of equality of the coefficients in each case.

It is worth noting that these regressions differ from a standard differences-in-differences analysis in that we do not have a simple treated versus control comparison. Our comparison countries offered their airframe producers some level of IP protection in the pre-1926 period, so we do not expect innovation in those locations to match pattern that we observe in the United States In fact, we can see that innovation in the United States was slower than

[30] We examine the case of the other major leader in airframes, France, in Appendix G.

[31] As with equation (8), an examination of the residuals shows no evidence of correlated errors for observations within the same year but no clear evidence of serial correlation across years.

Table 1: Results for Airframe Innovation in the United States Before and After 1926

	US Only		Comparison to UK and Japan				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Outcome	Wing	Wing	Wing	Wing	Wing	Wing	Wing
(in log)	Load	Load	Load	Load	Load	Load	Load
Before 1926 × year × US	0.001	0.014	-0.030	-0.042	-0.023	-0.023	-0.030
	(0.021)	(0.010)	(0.021)	(0.012)	(0.010)	(0.006)	(0.006)
After 1926 × year × US	0.079	0.066	0.047	0.009	0.044	0.034	0.058
	(0.004)	(0.006)	(0.006)	(0.009)	(0.021)	(0.013)	(0.039)
weighted by output	yes	no	yes	no	yes	yes	yes
year fixed effects	no	no	no	no	yes	no	yes
engine controls	no	no	no	no	no	yes	yes
F-statistic	13.1	19.7	13.4	20.2	8.3	17.6	4.9
p-value	0.002	0.000	0.001	0.000	0.006	0.000	0.031
observations	75	75	155	163	155	129	129

Notes: The dependent variable in each column is the log wing load, which calculated as gross weight divided by wing area. All specifications use new designs from 1916 to 1938 control for the level of airframe innovation in each country as well as a trend in technological progress over the sample period. Column 1 reports results weighted by the total number of airframes sold and column 2 shows unweighted results based on estimating equation (8) only for the United States for airframes.. Column 3 reports results weighted by the total number of airframes sold and column 4 shows unweighted results based on estimating equation (9) comparing the United States to both the United Kingdom and Japan. Columns 5 through 8 include additional control for a different trend in technological progress before and after 1926 (column 5), year fixed effects (column 6), the number of engines and engine horsepower (column 7), and year fixed effects plus engines controls (column 8). In each column the reported F-statistic and p-value are for the null hypothesis that the estimated coefficients for the rate of technological progress before and after 1926 are equal. Standard errors are clustered at the country-year level.

the comparison countries before 1926. After 1926, the more rapid gains in the United States relative to comparison countries suggests that, once the military had commited to buying airframes from the firm that produced the design, the US innovation system was more effective than the system in place in comparison countries. Given these features, main benefit of comparing across countries is that it helps us control for other broad changes that might have caused airframe innovation rates to differ after 1926 relative to before.

So far we have focused on a single measure of innovation (wing load) and type of aircraft (fighters). Of course, there were several alternative dimensions of performance or different types of aircraft that militaries considered and, in a few cases, targeted for improvement. In general, alternative measures of airframe performance (e.g., maximum speed, altitude ceiling) tend to be positively correlated with wing load. In Appendix E.3, we show that a similar pattern of technological progress is apparent using other performance measures such as maximum speed, as well as when calculating the first principal component across all available performance measures.[32] We also show that similar results are obtained for bombers and reconnaissance airframes. In general, the results indicate the performance of US airframes in these market segments was slower before and accelerated after 1926 relative to the comparison countries.

In Appendix E.5 we also examine the pattern of performance improvements by company, focusing on the three most important US producers: Boeing, Curtiss and Douglas. Those results show that, even within company, we tend to see the same pattern of accelerated performance improvements in the years just after 1926, relative to the years just before.

The technological progress shown in these results reflect the wide range of improvements introduced into airframes during this period. Wood gave way to metal in structural elements and fabric covering was replaced by monocoque designs where the stressed metal skin contributed to the plane's structural integrity. Cockpits were covered, wing shapes changed, flaps and slots were added, wing fairings were introduced to reduce interference between the fuselage and the wing root, new engine cowlings and cooling systems reduced engine drag, retractable landing gear were introduced, etc. And whereas the United States was a technological laggard in the early 1920s, by the 1930s it had become a leader in both military and civilian airframe design.

It is useful to digress slightly here in order to trace out in more detail the interplay between military and civil designs during the period that we study. In the United States, the moribund rate of progress in military designs in the early to mid-1920s meant that many innovative designs were produced for the civil market. Emblematic of the importance of civil designs during period of military stagnation is the path-breaking Lockheed Vega of

[32]Since we do not observe each performance measure for all new designs we first use multiple imputation to impute missing data assuming a multivariate normal distribution. Specifically, we use the `mi impute mvn` command in `Stata`© and the same independent variables as in equation (9) as predictors. We then find the first principal component and use it as the dependent variable.

1927, designed by Jack Northrop. The Vega was a single-engine high-wing monoplane with a wooden monocoque fuselage, wooden internally-braced wings, enclosed cockpit, and clean, aerodynamic lines.

However, by the early 1930s, military designs were pulling even with civilian models. At Boeing, the firm began production of an all-metal monoplane fighter, the XP-9, in 1928. While the XP-9 was not successful, its design was incorporated into a civil design, the Monomail (Boeing Model 200), which flew in 1930 (Bowers, 1989).[33] The Monomail in turn provided inspiration for a new set of bomber designs, the B-9 family. The Boeing B-9 bomber family (first flown in 1931), followed closely by the Martin B-10 of 1932, represents an important turning point in the relationship between U.S. military aircraft design and the civil/commercial market. The designs of these new bombers clearly reflected the aerodynamic legacy of planes like the Monomail and the Vega, but at a much larger scale and with a two-engine design. These aircraft incorporated key advances, such as the installation of the two engines in-line with the wings, rather than slung below as in the Ford Trimotor.[34]

The designs for the B-9 and the Martin B-10 provided the template for modern commercial aircraft. When the Army ultimately favored Martin's B-10 over Boeing's B-9, Boeing took the lessons from the B-9 design and produced the Boeing Model 247. The Model 247, first flown in February 1933, was the world's first modern airliner, with a low-wing multi-engine all-metal monoplane design that would eventually become standard. It was soon followed by the Douglas DC-1, first flown in July 1933, which improved the basic template set by the Model 247 and laid the foundation for the DC-3 of 1935, the most successful commercial aircraft of the period.

This brief description highlights two distinct phases in the interplay between civilian or commercial and military aircraft design. In the first phase, from World War I up until the late 1920s, innovative civil aviation designs such as the Lockheed Vega led military designs. In the second phase, starting in the late 1920s, military designs incorporated the previous advances made into civil aviation and pushed these advances into all-metal and larger multi-engine aircraft. This phase, epitomized by the Boeing B-9 and Martin B-10 bomber families, opened the door for the new commercial designs that followed.

In Appendix E.6 we provide empirical support for the patterns highlighted in the qualitative discussion above. We do this by comparing innovation rates after 1926 among producers focused heavily on the military market (Boeing, Curtiss, Douglas and Martin) to innovation by the largest firms focused primarily on the civil market (Fairchild and Lockheed).[35] This

[33]The Monomail actually flew before the XP-9, despite the fact that the XP-9 was designed first, because the more complex military design took longer to produce and required more modifications.

[34]Setting the engines well forward of the wing, there was less interference with the wing's lifting capacity, while putting the engines in-line rather than below the wing substantially reduced drag (Miller and Sawers, 1970, p. 67).

[35]This is possible after 1926 but not before, because we observe too few designs by civil producers in the earlier period.

comparison shows that indeed designs by firms focused on the civil market were more advanced in 1926, but that innovation was more rapid among military producers after 1926, so that by the mid-1930s the performance of military designs exceeded that of the best civil producers.

This narrative helps explain why the first major advances toward modern commercial aircraft were made by companies, Boeing and Douglas, that had previously been focused primarily on producing military designs. This fact is often overlooked, but should not be surprising. Both firms had gained experience in producing large multi-engine military aircraft, either for bombing or long-range observation, in the late 1920s and early 1930s, setting the stage for their success in the commercial market. For Boeing, in particular, there is a clear path leading from the B-9 bomber to the 247 airliner. It is useful to contrast this experience with Lockheed, a firm focused almost entirely on the civilian market. Lockheed had been the source of the most innovative designs in the mid-1920s, and Lockheed continued to produce excellent new designs in the early 1930s, such as the Altair and Orion, yet it remained focused on smaller single-engine aircraft. As a result, Lockheed was late in adopting the twin-engine design that would eventually dominate commercial aviation.[36] All of these patterns reinforce the central role that military demand played in aircraft development during this period.

5.2 Aero-Engines

Next, we examine innovation in aero-engines. Figure 1B presents the pattern of performance improvement graphically and indicates a generally declining rate of technological progress in aircraft engines in the United States after 1926, relative to the years before 1926.[37] More formally, we estimate regressions similar to equation (8) for the United States only. The results are shown in the first two columns of Table 2 using horsepower divided by engine displacement (column 1) and horsepower divided by weight (column 2). Respectively, in each column, the annual rate of innovation slowed from 6.3 and 5.9 percent before to 3.7 and -1.6 percent after 1926. The associated F-statistic (and p-value) confirm that we can reject the null hypothesis for the equality of these coefficients.

This results for the United States contrast with engine improvements in the United Kingdom, Germany, and Italy over the same period. The remaining columns of Table 2 shows the results from estimating versions of equation (9). Columns 3 and 4 compare the United States to the United Kingdom, Germany, and Italy. In both cases, engine improvements are faster in the United States before 1926 and slower after. Column 5 adds year fixed effects and column 6 includes controls for whether the engine was air- versus liquid-cooled. Columns 7 and 8 confirm that controlling for both year fixed effects and engine type using either horsepower per displacement or by weight does not alter the interpretation of the results.

[36] It entered this market in 1934, two years behind the 247, with the moderately-successful Electra.

[37] In addition, there is also a decline in the number of new designs in the United States.

Table 2: Results for Aero-Engine Innovation in the United States Before and After 1926

	US Only		Comparison to UK, Italy, and Germany					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Outcome	HP per	HP per	HP per	HP per	HP per	HP per	HP per	HP per
(in log)	Disp.	Lbs.	Disp.	Lbs.	Disp.	Disp.	Disp.	Lbs.
Before 1926 × year × US	0.063	0.059	0.016	0.033	0.022	0.023	0.025	0.053
	(0.006)	(0.015)	(0.007)	(0.016)	(0.007)	(0.007)	(0.006)	(0.016)
After 1926 × year × US	0.037	-0.016	-0.010	-0.042	-0.012	-0.012	-0.011	-0.038
	(0.012)	(0.037)	(0.012)	(0.036)	(0.013)	(0.012)	(0.013)	(0.026)
year fixed effects	no	no	no	no	yes	no	yes	yes
liquid- vs. air-cooled	no	no	no	no	no	yes	yes	yes
F-statistic	4.0	3.5	4.2	3.9	5.3	7.3	6.4	8.5
p-value	0.06	0.08	0.04	0.05	0.02	0.01	0.01	0.00
observations	67	35	441	333	441	441	441	333

Notes: The dependent variable in columns 1, 3, and 5 through 7 is the log of horsepower divided by engine displacement. The dependent variable in columns 2, 4, and 8 is the log of horsepower divided by engine weight. All specifications use new designs from 1916 to 1938 for each country and control for the level of aircraft innovation in each country as well as a trend in technological progress in each country before and after 1926. Columns 1 and 2 report the results for estimating a version of equation (8) only for the United States for aircraft engines using the log of the indicated dependent variable. Columns 3 and 4 report the results for estimating a version of equation (9) comparing the United States to the United Kingdom, Germany, and Italy using the log of the indicated dependent variable. Column 5 adds year fixed effects and column 6 adds controls for whether the engines was liquid-cooled (versus air-cooled) interacted with a post-1926 indicator. Columns 7 and 8 include both year fixed effects and controls for engine type. In each column the reported F-statistic and p-value are for the null hypothesis that the estimated coefficients for the rate of technological progress before and after 1926 are equal. Standard errors are clustered at the country-year level.

Combined with the reported F-statistics (and p-values), these results suggest that gains in engine performance slowed in the United States after 1926 relative to before and relative to other countries.

As with airframes, our cross-country comparison of aero-engine performance does not reflect a simple comparison of treated vs. untreated locations. Each country had a different IP regime related to aero-engines during the study period, so we should not expect parallel trends in innovation before 1926. Given this, the cross-country comparison serves mainly to help us control for other broad factors that may have influenced aero-engine innovation.

In fact, it is interesting to see that innovation was more rapid in the United States in the pre-1926 period. We interpret this as reflecting the fact that engine makers benefited from IP protection while airframe producers did not. In our model this represents an ideal scenario for incentivizing aero-engine innovation. After 1926 this advantage disappeared and we see that the U.S. aero-engine innovation rate is not statistically distinguishable from what we observe in the comparison countries.

While US engine producers introduced pathbreaking new designs prior to 1926–such as the Pratt & Whitney Wasp air-cooled radial engine–subsequent technological progress often involved more modest evolutions of existing designs (Taylor, 1971). American engine firms were innovative during the late 1920s and 1930s, but their attention was mainly focused on producing more durable designs with lower maintenance costs for the commercial market, rather than higher-performance designs for the military (Miller and Sawers, 1970, p. 86-7).[38]

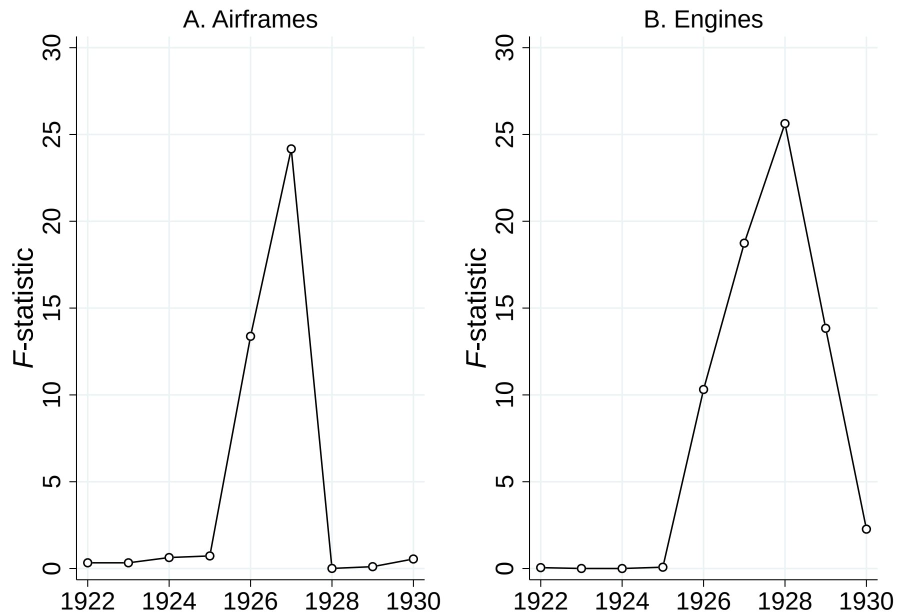
One consequence of the limited attraction of the military market after the mid-1920s is that the leading US aero-engine producers essentially abandoned the production of new liquid-cooled engine designs. Air cooled engines were simpler to build and maintain, but they also created more drag than liquid-cooled designs. The decision to abandon innovation in liquid-cooled engines would turn out to be an important one, as liquid-cooled engines would prove dominant for top-line fighter designs during World War II, as we discuss in Section 7.

5.3 Placebo Results

The analysis above provides evidence that airframe innovation accelerated in the United States after 1926, while aero-engine innovation stagnated. Thus far, we have relied on our understanding of the industry to pinpoint the policy change to 1926-27. However, it is worth considering the results using "placebo" policy changes imposed in different years. The results of allowing for placebo changes are shown in Figure 2, which plots an F-statistic based on the null hypothesis for the equality of β_{before} and β_{after} coefficients from a version of equation (9) comparing the United States to all countries for an assumed break for each year between 1922 and 1930. For airframes, Panel A shows a break after 1926 that reaches a peak in 1927

[38]Commercial engine use differed from military use in important dimensions. Airlines flew much more often, but engines only had to operate at peak power for takeoff. Military combat aircraft flew less often, but peak power was demanded more often, not just at takeoff but also at altitude.

Figure 2: Placebo for Airframe and Aircraft Engine "Treatment Year"



Notes: Each panel reports the F-statistic based on the null hypothesis for the equality of β_{before} and β_{after} coefficients from a version of equation (9) comparing the United States to all countries for an assumed break for each year between 1922 and 1930. Panel A shows the results for airframes using the log of wing load as the dependent variable. Panel B shows the results for aero-engines using the log of horsepower divided by displacement as the dependent variable. Standard errors are clustered at the country-year level.

and is consistent with a lag in development time for new airframes designs after the 1926 policy change. For engines, Panel B results shows that the F-statistic is lowest from 1922 to 1925, increasing until 1928, and declining afterward. In both cases we interpret these results as providing evidence suggesting that the key shifts in the industry occurred around and just after 1926.[39]

6 Alternative Explanations

The results for airframes and aero-engines show a clear pattern of increasing and decreasing rate of innovation, respectively. The pattern is similar for the United States alone or comparing the United States to other countries. In Section 3, we presented a theory that described one mechanism through which providing IP protection to airframe producers may increase innovation in airframes and simultaneously decrease innovation in aero-engines. This theory is attractive in part because it is simple and relies on straightforward economic (profit) incentives. Below we discuss potential alternative explanations and an additional

[39]In Appendix E.4, we show the results of alternative placebo treatment years separately for each country for both airframes and aero-engines.

implication of the theory we can use to provide further support for our preferred explanation.

Quality substitutes: One alternative explanation for our findings is that the quality of airframes and the quality of aero-engines are substitutes. In this theory, faster improvement in airframes could reduce the incentive for innovation in aero-engines. However, our study of the aircraft industry during this period suggests that airframe and engine performance were more likely to be complements than substitutes. For example, better engines could make planes faster, but with faster speeds poor aerodynamics became costlier in terms of lost efficiency and increased stress on the airframe. Conversely, better aerodynamic performance made airframes more efficient, but these efficiency gains were even greater at the higher speeds that more powerful engines could achieve. We view this explanation as unlikely, although we cannot not rule out some level of substitutability or complementarity in quality between airframe and engine technology.

Spillovers from civil/commerial market: Another potential concern is that the change in innovation patterns may have been driven by policy changes affecting the civil and commerical aviation market, such as the Air Commerce Act. As discussed in Section 2, the fact that we focus on a high-performance segment of the market where the military was the dominant buyer suggests that this is unlikely. Further evidence against this explanation is offered in Appendix E.6. After 1926, it was firms focused on the military rather than the civil/commercial market that drove innovation in both airframes and aero-engines. Not only did firms selling mainly to the military innovate more rapidly after 1926, but within these firms the civil designs they did produce tended to follow rather than lead the performance of military designs. These patterns are not consistent with our main results being driven by changes occurring in the civil/commercial market.

Increase in demand: Another potential alternative theory is that the patterns we document were due to changes in the overall government demand for military aircraft after 1926. Greater demand could explain the acceleration in airframe performance. However, this story is difficult to reconcile with the slow-down in engine performance. Thus, while the increase in demand was likely to affect military aircraft market during this period, it is story is not consistent with our key empirical findings.

Change in procurement: Alternatively, innovation activity observed around 1926 could have been due to changes in procurement practices, rather than property rights. However, the records of the Air Corps Procurement Board do not indicate other significant changes in procurement practices beyond the shift from competitive bidding to negotiated contracts. In addition, the fact that a number of the important designs produced after 1926 were private ventures rather than the result of government contracts for experimental aircraft or clearly-defined design competitions suggests this channel is unlikely to be driving our results (see Appendix D for further details).

Within-company learning: Finally, airframe producers may have experienced learning that allowed for the production of better designs over time. As with the explanation emphasizing increased government demand, this explanation is not consistent with the slowdown in engine performance nor does it explain relative differences between the United States and foreign airframe producers.

None of these alternative theories provide a compelling explanation for all of our empirical findings, although we cannot rule out any of these explanations entirely. To provide additional support for our preferred explanation, the next subsection discusses and tests an additional prediction that arises from our model.

6.1 Additional evidence supporting the theory

In this section we examine additional predictions emerging from our theory in order to provide direct evidence that the mechanisms we highlight were at work, and meaningfully important, in the setting we consider. Specifically, we focus on the prediction that extending IP protection to airframe producers creates new incentives for merger activity between airframe and engine makers. This is a useful prediction to focus on because it emerges naturally from the theory we have proposed but is unlikely to emerge from the competing theories described above.

Our empirical setting provides an excellent opportunity for looking at the endogenous response of merger activity to changes in IP protection. In particular, the type of active antitrust enforcement that may have slowed down or blocked merger activity in other settings was almost completely absent in the period we study. Antitrust authorities were reluctant to oppose mergers in the 1920s after having suffered major defeats in their efforts to break up US Steel between 1915 and 1920 as well as in cases against United Shoe Company in 1918 and American Can Company in 1916 (Scherer and Ross, 1970, p. 457-8). Thus, the firms we study were essentially free to pursue mergers.

In order to track merger activity, we construct a set of firm histories covering all of the important US producers of airframes and military engines. In addition, to provide a point of comparison we construct similar firm histories for British and French military airframe and engine manufacturers, as well as US manufacturers of civil airframes and aero engines. These firm histories have been constructed using a wide variety of sources, though much of the information comes from the Jane's yearbooks.

Figure 3 describes the pattern of merger activity among U.S. firms active in military airframe or engine production. We consider activity from 1920 up to 1934, the year in which Roosevelt's administration intervened in the industry to break up United Aircraft. At the top we have the two major US military aero-engine producers after 1926, Wright Aeronautical and Pratt & Whitney. Curtiss also produced some military aero-engines during this period, though the firm was primarily focused on airframes. Contemporary sources indicate that these were essentially the only firms capable of producing the high-performance aero-engines demanded by the military.

By 1929, both of the independent aircraft engine-makers had merged with airframe producers. Wright Aeronautical merged with Curtiss, the largest airframe producer, as well as what were previously Huff-Daland/Keystone, Loening, and Travel Air, to form the Curtiss-Wright Corporation. Pratt & Whitney merged with Boeing and what were previously Chance-Vought, Stearman, and Sikorski to form United Aircraft.[40]

The merger activity just a couple of years after the 1926 change in IP protection stands out relative to the period before and after. Of course, a natural worry is that there were some other changes taking place in the aircraft industry that caused the distinct pattern of merger activity described in Figure 3. For example, we may worry that these mergers were driven by the "Lindbergh boom" in civil and commercial aviation that took place in the United States in the late 1920s.[41] One way to address this issue is to compare the pattern observed among military aero-engine producers in the United States to the pattern of merger activity among firms focused on the civil market. For airframe producers, we can see the most important of these firms in Figure 3. Fairchild and Lockheed, for instance, were mainly focused on the civil market during this period. We see no merger activity among this group. We have also constructed firm histories for the most active civil aero-engine firms in the United States in the 1920s and 1930s which we describe in Appendix F. Among engine producers, only Wright and Pratt & Whitney merged with an airframe producer in the second half of the 1920s. No similar pattern is observed among producers focused primarily on the civil or commercial market. In fact, we do not observe any mergers between civil airframe and aero-engine producers during our study period. Thus, it does not appear that the merger activity observed among military airframe and aero-engine producers in the late-1920s was the result of broader changes in the US aircraft industry.

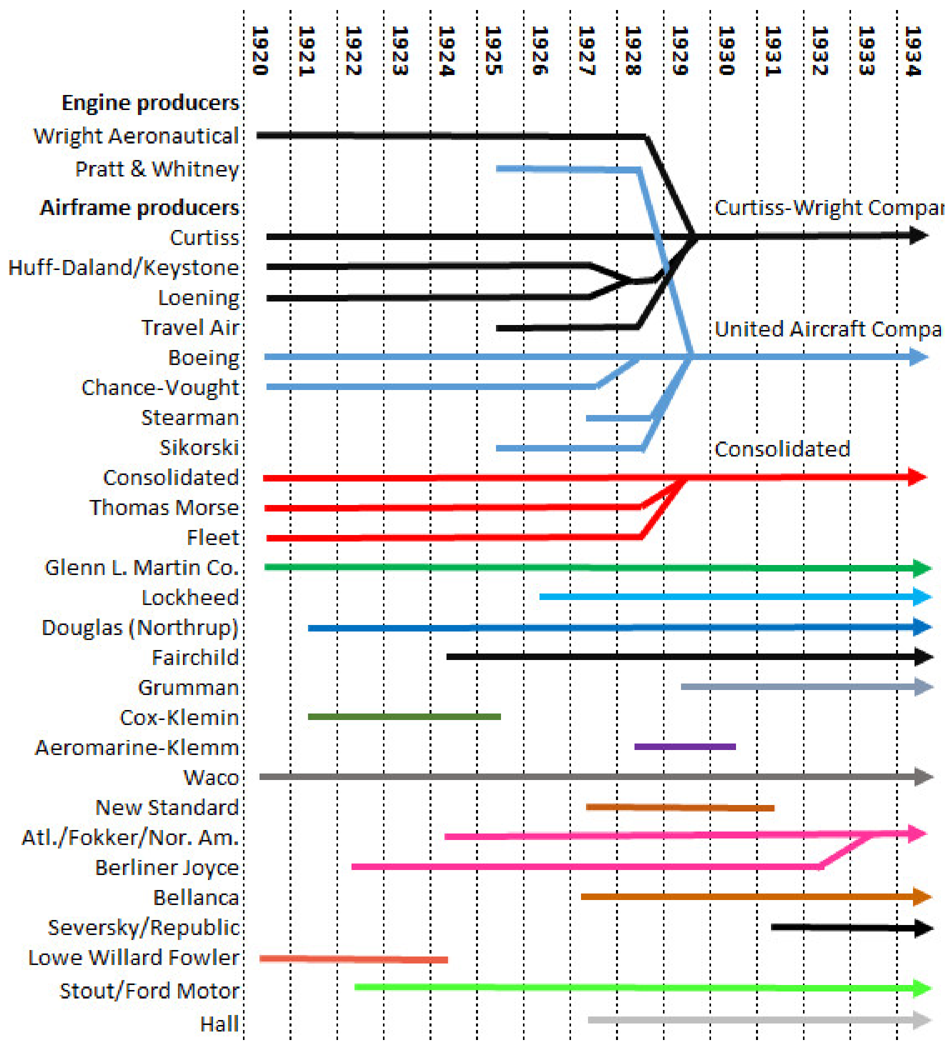
We may also worry that the merger activity in the United States was a result of a broader pattern of changes in military aviation technology that took place during this period. To help rule out this concern, we compare the pattern of merger activity in the United States to the pattern in Britain and France. For the United Kingdom, our firm histories show that none of the major military aero-engine producers (Bristol, Rolls-Royce, Napier, de Havilland) merged with airframe producers in the second half of the 1920s (see Appendix F).[42] In France,

[40]United Aircraft also included an airline, United, which originated as part of Boeing. In 1934, in response to charges of collusion from smaller airline operators, President Roosevelt revoked all private airmail contracts (Patillo, 1998, p. 87). Initially, the Army Air Corps filled in by flying the airmail routes. However, the Air Corps was ill-equipped to take on this job on such short notice. After a series of accidents resulted in the deaths of twelve pilots, air mail was returned to commercial operators under the Airmail Act of 1934. This legislation contained a provision which banned airmail carriers from also producing aircraft, and ultimately forced the breakup of United Aircraft.

[41]This boom did appear to contribute to merger activity among airlines, but often these mergers did not include aircraft producers.

[42]The only merger activity that took place in Britain int he second half of the 1920s was purchase of Avro, an airframe producer, by the integrated company that included Armstrong Siddeley, an aero-engine maker,

Figure 3: Entry, Exit, and Mergers of Airframe and Engine Producers



the two main military aero-engine producers, Hispano-Suiza and Gnome-Rhone, did not engage in airframe production during our study period. Of the other three important aero-engine producers (Renault, Salmson, Lorraine-Dietrich), only Lorraine-Dietrich merged with an airframe producer during the study period, and this occurred under heavy government pressure. That merger, with Hanriot in 1930, only lasted until 1933. In summary, in neither Britain nor France do we observe a pattern of mergers between important military aero-engine producers and airframe producers similar to what we see in the United States in the late 1920s. This suggests that the pattern of merger activity observed in the United States was not likely to have been a consequence of other changes occurring in the military aircraft sector.

Our theory also makes additional predictions about the pattern of mergers that we should observe, conditional on mergers occurring. In particular, in the model, if firms are allowed to merge after their innovation outcomes are realized, then we should expect to observe mergers between firms that are the leading producers in the same market segments. In addition, if firms merge before making innovation decisions, then we should expect them to coordinate their innovation investments in the same market segments. Empirically, these predictions imply that we should expect mergers to take place between airframe and aero-engine firms that were selling products that were used together in the pre-1926 period, and that after the merger we should expect the airframes and engines produced by merged firms to be even more likely to be used together.

Table 3 provides evidence on the pattern of matching between products produced by the different airframe and aero-engine firms. Each cell in this table describes the share of each airframe producer's output that was used together with engines from a particular aero-engine firm. Prior to 1926, we see that Boeing airframes were relatively more likely to be used with Pratt & Whitney engines, while Curtiss airframes were more likely to use Wright engines. Given this, the fact that Boeing subsequently merged with Pratt & Whitney while Curtiss merged with Wright matches what our theory would predict. In addition, after 1928, we see that these matching patterns were even stronger, a pattern that is also consistent with what the theory would lead us to expect (though it is not unexpected and may be expained in a variety of other ways).

Both the timing of merger activity between airframe and aero-engine producers as well as the pattern of firm-to-firm matching are consistent with the predictions of our theory. This provides additional support for the theory we have proposed, particularly given that these predictions are not likely to emerge from natural alternative theories. The fact that we find support for the merger predictions generated by our model suggests that the underlying

and Armstrong Whitworth, and airframe manufacturer. This purchase was precipitated by a mega-merger between two giant armaments firms, Vickers and Armstrong Whitworth, which resulted in the spin-off of their aircraft-related operations. Two other important aero-engine firms, Bristol and de Havilland, already produced both airframes and aero-engines at the beginning of the 1920s.

Table 3: Engines Used By Airframe Producers Before and After 1929

	Enginer Producers:					
	Pratt & Whitney		Wright		Other Engine	
Airframe	(1)	(2)	(3)	(4)	(5)	(6)
Producers:	Pre-1929	Post-1929	Pre-1929	Post-1929	Pre-1929	Post-1929
Boeing	49.0	99.5	8.9	0.5	42.2	0.0
Curtiss	16.3	24.1	25.2	75.9	58.5	0.0
Other Airframe	7.1	51.6	47.2	42.7	45.7	5.7

Notes: The table shows the fraction of output by Boeing, Curtiss, and “other” airframe producers that use Pratt & Whitney, Wright, and “other” engines before and after 1929.

mechanisms were an important part of the forces at work. That said, we cannot rule out that other mechanisms played a role.

7 Implications

The main goal of this paper is to provide evidence for the direct and spillover effects of IP protection. More speculatively, our approach also provides a natural way to evaluate where the US aircraft industry would have been in the absence of the change in IP protection that is the focus of this paper. By accelerating airframe innovation in the interwar period, the 1926 Air Corps Act may have played an important role in determining the readiness of American air power for World War II–a conflict where air power played a crucial role.

In Figure 4 we use our empirical estimates to reconstruct actual and counterfactual trends in airframe and engine innovation in the United States, and to compare the United States to other countries. Panels A and B of Figure 4 show the result of this exercise for airframes (fighters) and aero-engines, respectively. In Panel A, the solid lines show the actual trends in wing load for the United States before and after the 1926 policy change and the dashed line shows the counterfactual trend that might have prevailed after 1926 in the absence of the policy change. At the right of this panel we note the average wing load for new designs produced by comparison countries between 1935 and 1938. Though speculative, this figure suggests that the United States would have been far behind these other countries–including World War II belligerents–in terms of airframe technology, without the IP protection for airframes granted in 1926. In Panel B, a similar exercise for engines shows that US engine performance was comparable or just below comparison countries by the mid-1930s. However, if the pre-1926 trend had continued instead, the United States would have possessed better engine technology.

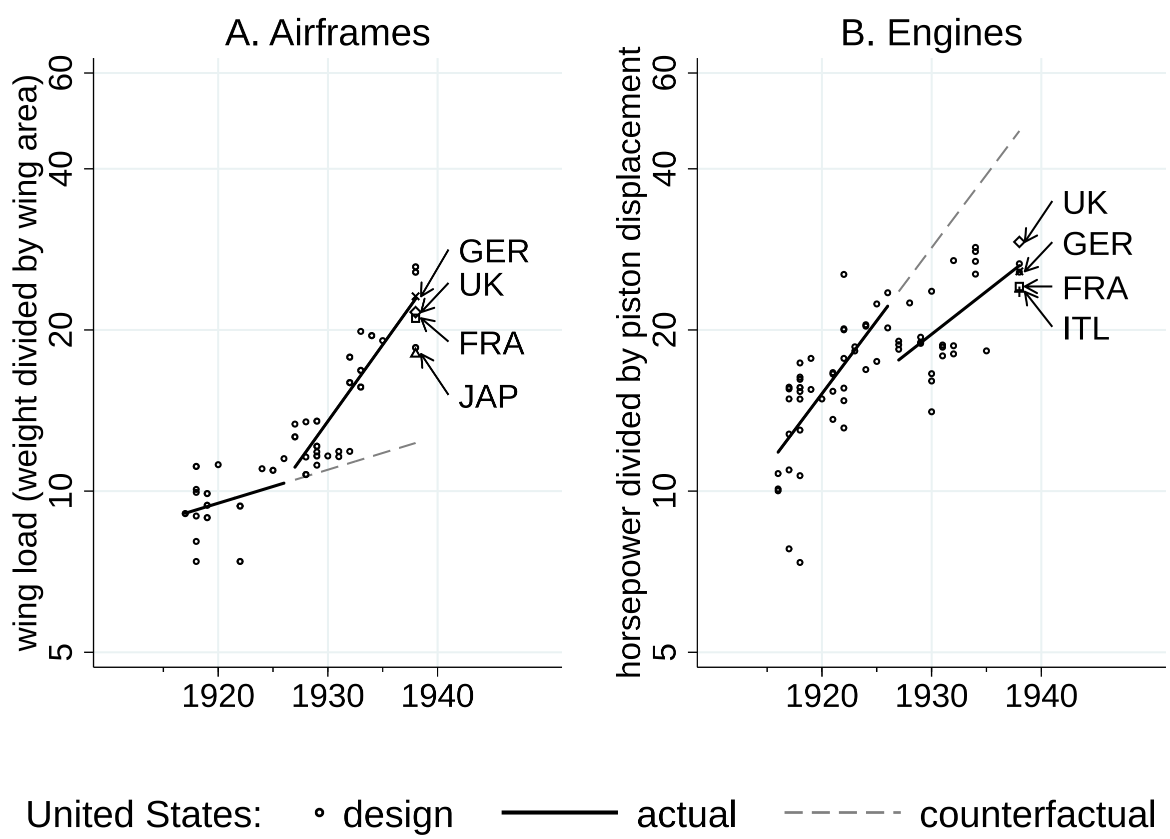
The most visible consequence of the slowdown in aero-engine development in the United States in the 1930s was the almost complete abandonment of liquid-cooled designs. Liquid-cooled engines, while expensive and difficult to maintain, proved to be vital for the highest-performance fighter aircraft during the war because they allowed more aerodynamic designs than air-cooled engines.

The P-51 Mustang, the most effective high-performance fighter produced by the U.S. during World War II provides a striking example of the consequences of these changes. While the P-51 airframe was designed in the U.S., it only achieved its full potential when paired with the British-designed Rolls-Royce Merlin liquid-cooled engine.[43] By the late-1930s, no U.S. engine design could match the performance, particularly at altitude, of the Rolls-Royce Merlin engine family, or the Germany equivalents (the Diamler-Benz 601/603/605 and Junkers Jumo 213 engines).[44]

[43] Many of these were produced on-license in the U.S.

[44] The only successful high-performance liquid-cooled engine designed in the United States in the 1930s, the Allison V-1710, emerged almost by accident. The design was originally developed for airships rather than

Figure 4: Comparing Actual and Counterfactual Trends in Innovation for the United States



Notes: Each panel shows the actual trend in innovation before 1926 and the actual and counterfactual trend in innovation after 1926 in the United States for airframes (Panel A) and engines (Panel B). For airframes the measure of innovation is wing load; for engines the measure of innovation is horsepower divided by engine displacement. In addition, each panel also plots the average innovation for select countries between 1935 and 1938: the United Kingdom, France, Japan, and Germany (Panel A) and the United Kingdom, France, Germany, and Italy (Panel B).

8 Conclusion

The relationship between IP protection and innovation has important implications for economic growth. In this paper we show that the effects of IP protection can be both *direct* (i.e., IP increases the incentive to innovate in areas where IP is granted) and *indirect* (i.e., IP increases or decreases innovation in areas where technology is either substitute or complement). We use the setting of the interwar aircraft industry in the United States to show that both effects are quantitatively important. In particular, granting IP protection for airframes increased the rate of innovation for airframes and decreased the rate of innovation for complementary aero-engines. We also show that this led to mergers between airframe and aero-engine producers. Together, we interpret these results as support for an underlying mechanism that fundamentally connects innovation decisions and market structure.

Although our empirical evidence is derived from a particular setting, the mechanism we emphasize is general and relevant in all markets where products are linked as complements or substitutes. This has important implications for understanding how changes in IP protection affect innovation and market structure, the interaction with antitrust policy, and the potential consequences for economic growth. Our results are useful to researchers comparing similar goods in the context of difference-in-difference analysis to evaluate the efficacy of changes in IP: comparisons of goods that are complements (substitutes) will to tend to overstate (understate) estimated treatment effects. Our results also add to existing work suggesting that in some cases IP protection may provide property rights to too many agents, creating patent thickets (Shapiro, 2000) and an anticommons (Heller and Eisenberg, 1998). While we do not argue that property rights are too strong in our setting, we highlight a cost of providing IP protection to weigh against potential benefits. Finally, we provide evidence that institutional change related to IP played an important role in determining the position of the US aircraft industry in the world on the eve of World War II.

airplanes, and the builder, Allison (a division of General Motors), was not a major aero-engine producer. This engine would see substantial service during World War II, but was never as effective, particularly at high-altitudes, as foreign engines like the British Rolls-Royce Merlin engine family and the German Diamler-Benz 601/603/605 and Junkers Jumo 213 engines.

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Appendix

A Theory Appendix

A.1 Proof of equilibrium existence and uniqueness

To prove equilibrium existence we need to show that there exists a I_{mjf} such that equation (5) is satisfied when $I_{mjF'} = I_{mjF}$. Given our assumptions on $\phi(\cdot)$ we know that the left-hand side of equation (5) is strictly decreasing in I_{mjF}, that $\lim \phi(I_{mjF}) \to +\infty$ as $I_{mjF} \to 0$, and that $\lim \phi(I_{mjF}) \to 0$ as $I_{mjF} \to +\infty$. It remains for us to study how the right-hand side of equation (5) evolves as I_{mjF} changes. To simplify the notation, define $x = \phi(I_{mjF})$, which is a strictly increasing function of I_{mjF}.

Focusing only on the terms behind the summation operator in equation (5), we can expand this term to obtain,

$$
\begin{array}{ll}
\frac{(N-2)!}{0!(N-2)!} & \left(\frac{1-\phi(I_{mjL})}{1} + \frac{\phi(I_{mjL})}{2}\right) x^0(1-x)^{N-2} \\
\frac{(N-2)!}{1!(N-3)!} & \left(\frac{1-\phi(I_{mjL})}{2} + \frac{\phi(I_{mjL})}{3}\right) x^1(1-x)^{N-3} \\
\frac{(N-2)!}{2!(N-4)!} & \left(\frac{1-\phi(I_{mjL})}{3} + \frac{\phi(I_{mjL})}{4}\right) x^2(1-x)^{N-4} \\
\vdots & \\
\frac{(N-2)!}{(N-4)!2!} & \left(\frac{1-\phi(I_{mjL})}{N-3} + \frac{\phi(I_{mjL})}{N-2}\right) x^{N-4}(1-x)^2 \\
\frac{(N-2)!}{(N-3)!1!} & \left(\frac{1-\phi(I_{mjL})}{N-2} + \frac{\phi(I_{mjL})}{N-1}\right) x^{N-3}(1-x)^1 \\
\frac{(N-2)!}{(N-2)!0!} & \left(\frac{1-\phi(I_{mjL})}{N-1} + \frac{\phi(I_{mjL})}{N}\right) x^{N-2}(1-x)^0
\end{array}
$$

To see how this term changes as x changes, we take the derivative with respect to x to obtain:

$$
\begin{array}{rcl}
(N-2)\frac{(N-2)!}{0!(N-2)!}\left(\frac{1-\phi(I_{mjL})}{1}+\frac{\phi(I_{mjL})}{2}\right)(1-x)^{N-3} & & \\
\frac{(N-2)!}{1!(N-3)!}\left(\frac{1-\phi(I_{mjL})}{2}+\frac{\phi(I_{mjL})}{3}\right)(1-x)^{N-3} & - & (N-3)\frac{(N-2)!}{1!(N-3)!}\left(\frac{1-\phi(I_{mjL})}{2}+\frac{\phi(I_{mjL})}{3}\right)x(1-x)^{N-4} \\
2\frac{(N-2)!}{2!(N-4)!}\left(\frac{1-\phi(I_{mjL})}{3}+\frac{\phi(I_{mjL})}{4}\right)x(1-x)^{N-4} & - & (N-4)\frac{(N-2)!}{2!(N-4)!}\left(\frac{1-\phi(I_{mjL})}{3}+\frac{\phi(I_{mjL})}{4}\right)x^2(1-x)^{N-5} \\
 & \vdots & \\
(N-4)\frac{(N-2)!}{(N-4)!2!}\left(\frac{1-\phi(I_{mjL})}{N-3}+\frac{\phi(I_{mjL})}{N-2}\right)x^{N-5}(1-x)^2 & - & 2\frac{(N-2)!}{(N-4)!2!}\left(\frac{1-\phi(I_{mjL})}{N-3}+\frac{\phi(I_{mjL})}{N-2}\right)x^{N-4}(1-x) \\
(N-3)\frac{(N-2)!}{(N-3)!1!}\left(\frac{1-\phi(I_{mjL})}{N-2}+\frac{\phi(I_{mjL})}{N-1}\right)x^{N-4}(1-x) & - & \frac{(N-2)!}{(N-3)!1!}\left(\frac{1-\phi(I_{mjL})}{N-2}+\frac{\phi(I_{mjL})}{N-1}\right)x^{N-3} \\
(N-2)\frac{(N-2)!}{(N-2)!0!}\left(\frac{1-\phi(I_{mjL})}{N-1}+\frac{\phi(I_{mjL})}{N}\right)x^{N-3} & &
\end{array}
$$

Next, we reorganize to obtain,

$$
\begin{array}{r}
(1-x)^{N-3}\left[\frac{1-\phi(I_{mjL})}{2}+\frac{\phi(I_{mjL})}{3}-\frac{1-\phi(I_{mjL})}{1}-\frac{\phi(I_{mjL})}{2}\right]\frac{(N-2)!}{0!(N-3)!} \\
+x(1-x)^{N-4}\left[\frac{1-\phi(I_{mjL})}{3}+\frac{\phi(I_{mjL})}{4}-\frac{1-\phi(I_{mjL})}{2}-\frac{\phi(I_{mjL})}{3}\right]\frac{(N-2)!}{1!(N-4)!} \\
-x^2(1-x)^{N-5}\left[\frac{1-\phi(I_{mjL})}{3}+\frac{\phi(I_{mjL})}{4}\right]\frac{(N-2)!}{2!(N-5)!} \\
\vdots \\
-x^{N-5}(1-x)^2\left[\frac{1-\phi(I_{mjL})}{N-3}+\frac{\phi(I_{mjL})}{N-2}\right]\frac{(N-2)!}{2!(N-5)!} \\
+x^{N-4}(1-x)\left[\frac{1-\phi(I_{mjL})}{N-2}+\frac{\phi(I_{mjL})}{N-1}-\frac{1-\phi(I_{mjL})}{N-3}-\frac{\phi(I_{mjL})}{N-2}\right]\frac{(N-2)!}{1!(N-4)!} \\
+x^{N-3}\left[\frac{1-\phi(I_{mjL})}{N-1}+\frac{\phi(I_{mjL})}{N}-\frac{1-\phi(I_{mjL})}{N-2}-\frac{\phi(I_{mjL})}{N-1}\right]\frac{(N-2)!}{0!(N-3)!}
\end{array}
$$

In the first two term and last two terms of this expression, the value within the square brackets will always be negative. The remaining issue is what happens to the two terms in the middle. Note that the two middle terms will be unmatched only of there are no terms between them, which in the case of the expressions above will occur when $N = 7$. However, when $N = 7$, the two middle terms can be rewritten together as,

$$
x^2(1-x)^2\left[\frac{1-\phi(I_{mjL})}{4}+\frac{\phi(I_{mjL})}{5}-\frac{1-\phi(I_{mjL})}{3}-\frac{\phi(I_{mjL})}{4}\right]\frac{(N-2)!}{1!(N-5)!}
$$

which is also less than zero. We have not shown that the quantity inside the summation operator in equation (5) is a strictly decreasing function of $x = \phi(I_{mjF})$ and therefore also a decreasing function of I_{mjF}. This tells us that the right-hand side of equation (5) is an increasing function of I_{mjF}. It remains to show the location of the endpoints of this function at $I_{mjF} = 0$ and as $I_{mjF} \to +\infty$.

First consider the case in which $I_{mjF} = 0$, at which point $x = \phi(I_{mjF}) = 0$. At this point, the right-hand side of equation (5) simplifies to,

$$\left[\pi_{mj}\frac{(N-2)!}{0!(N-2)!}\left(\frac{1-\phi(I_{mjL)}}{1}+\frac{\phi(I_{mjL)}}{2}\right)\right]^{-1}$$

which is a finite positive number. When $I_{mjF} \to +\infty$ the right-hand side of equation (5) approaches,

$$\left[\pi_{mj}\frac{(N-2)!}{0!(N-2)!}\left(\frac{1-\phi(I_{mjL)}}{N-1}+\frac{\phi(I_{mjL)}}{N-2}\right)\right]^{-1}$$

which is also a finite positive number. Thus, we have shown that the right-hand side of equation (5) is strictly increasing function of I_{mjF} which begins with a positive value at $I_{mjF} = 0$ and asymptotes to a larger finite positive value as $I_{mjF} \to +\infty$. Since the left-hand side of equation (5) is strictly decreasing function of $I_{mjF'}$, approaches $+\infty$ as $I_{mjF'} \to 0$ and approaches 0 as $I_{mjF'} \to +\infty$, there must be a single unique equilibrium I_{mjF} that satisfies this equation when $I_{mjF'} = I_{mjF}$ conditional on I_{mL}. Figure A1 provides a graphical representation of these two curves.

Next, we need to show that there is a unique equilibrium combination of I_{mjL} and I_{mjF}. This is defined by equations (4) and (5) where $I_{mjF'} = I_{mjF}$. Using an approach similar to the one applied to equation (5) above, it can be shown that the I_{mjL} that satisfies equation (4) is a decreasing function of I_{mjF} that takes a positive finite value when $I_{mjF} = 0$ and approaches a smaller positive value as $I_{mjF} \to +\infty$. Similarly, the I_{mjF} that satisfies equation (5) is a decreasing function of I_{mjL} which takes a finite positive value at $I_{mjL} = 0$ and approaches a smaller positive value as $I_{mjL} \to +\infty$. Thus, these curves take the form described in Figure A2 with a unique equilibrium.

A.1.1 Proof that innovation investment is increasing in profits

An increase in profits will cause the right-hand side of equation (5) to decrease. In terms of Figure A1, this will cause the RHS line to move downward, resulting in a higher equilibrium I_{mjF} given I_{mjL}. In Figure A2, an increase in profits will cause an upward shift in both curves, implying higher equilibrium innovation investments for both the leader and the follower firms.

Figure A1: Equilibrium I_{mjF} defined by equation (5) given I_{mjL}

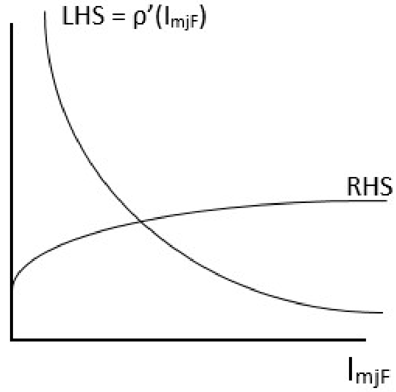
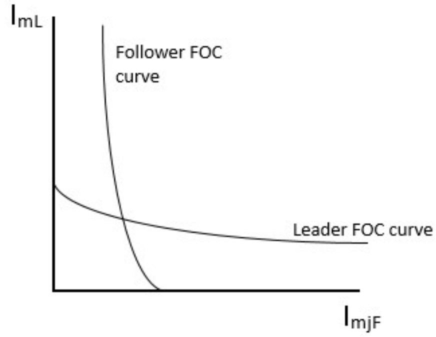


Figure A2: Equilibrium combination of I_{mjL} and I_{mjF} defined by equations (4) and (5)



B Empirical Setting Appendix

B.1 Further discussion of the patent pool

The aircraft patent pool was formed in 1917 to overcome a dispute between the Wright (later Wright-Martin) and Curtiss companies over key patents used for aircraft control (ailerons) to allow for increased wartime production. Wright held the most important patent and resisted the formation of the pool, but was ultimately forced to join by the government (Bittlingmayer, 1988; Katznelson and Howells, 2014). In order to compel Wright-Martin to join the pool the government used its position as the main buyer of aircraft. In addition, Congress passed legislation that would have condemned the patents, which gave government negotiators even more leverage.

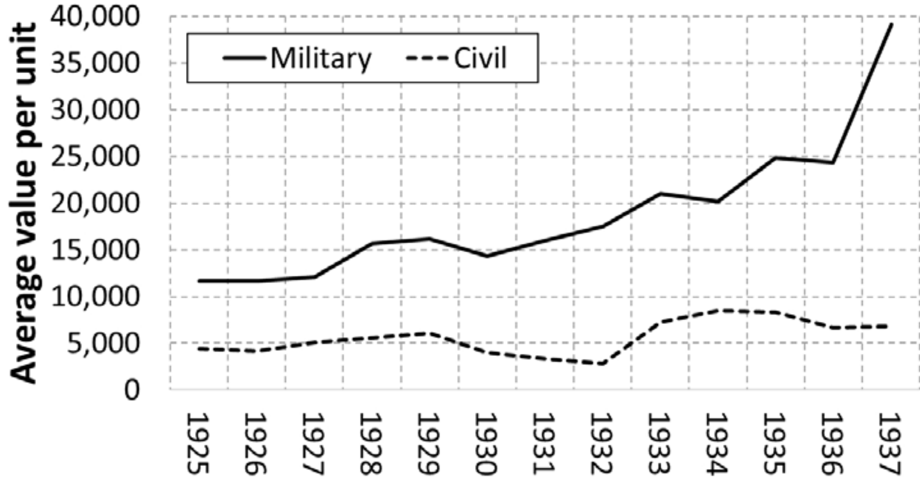
Pool members paid royalties to Wright and Curtiss (Bittlingmayer, 1988). These two companies were to receive up to \$2 million in royalties, later revised to \$1 million. Members had unlimited access to all patents in the pool (Patillo, 1998, pp. 35–36). When firms created new patents that were covered by the pool, they could receive some payments through an arbitration process. However, of the 750 patents covered by the pool, only 159 had been brought into arbitration by 1935. Of those, only 51 received cash awards, and the total awards for patents added after the formation of the pool was very small. Of the \$4,360,000 paid by the pool by 1933, only \$360,000 were paid for patents other than the original Wright and Curtiss patents.

The result of the patent pool was to essentially eliminate patent protection as an option for airframe producers. In fact, when the pool was eventually challenged in 1972, the government argued that the pool was anti-competitive mainly because it hampered competition in research and development (Bittlingmayer, 1988). This feature was also echoed at the time by key participants. For example, an internal document produced by the Curtiss company in May of 1923 argues in favor of maintaining the pool after the expiration of the initial patents. The document offers a number of arguments in favor of maintaining the pool, including that "The continuance of the Cross-License Agreement places all subscriber manufacturers on an equal footing competitively; promotes friendly intercourse; draws the manufacturing interests together; encourages cooperative spirit; and is in all respects a course strictly in accord with modern business practice."

B.2 Unit values of military vs. civil aircraft

Figure B1 shows average unit costs for military and civilian aircraft across the study period. Clearly military aircraft were more expensive than civil aircraft.

Figure B1: Unit Costs for Military and Civil Aircraft



Notes: Data from the *Aircraft Yearbooks* published by the Aeronautical Chamber of Commerce and generously shared by Paul Rhode.

B.3 Military aircraft procurement in the United States

This section presents some additional details on U.S. military aircraft procurement practices based primarily on the records of the U.S. Army Air Corps Procurement Board collected from the U.S. Government Archives. Most of these records start in 1926, with just a few available in 1925. The procurement board met regularly during the year, and thus the records of these meetings allow us to gain some understanding of how the procurement process unfolded.

Procurement planning for a year began early the year before with a discussion of the expected needs of the military for the following year. Starting with the budget allocated by Congress, and subtracting out the costs of any ongoing contracts from the prior year, the Board would then make a preliminary allocation of expenditures based on estimated prices.

The Board would then continue to meet on roughly a monthly basis to update and adjust the allocation. The following quote from the minutes of the Board's meeting on February 4, 1926 gives a sense of how this process worked:

> *In connection with the price submitted by the Douglas Company in the amount of $17,800.00 per unit for C-1 Transports, which would exceed the total amount allocated for 10 of this Type in the sum of $150,000, the advisability of the procurement or[sic] 10 transports was considered...In view of the foregoing, motion*

was unanimously adopted by the Board...that procurement be effected of (7) Transports. . .

A second example from the minutes of the Procurement Board's meeting on January 20, 1927 illustrates similar trade-offs:

Recommendations were submitted by the Chief, Material Division...for the procurement of (6) Pratt & Whitney Wasp Engines. The Board recommended approval of six (6) of these engines at a total estimated cost of $60,000.00. This item, however, will not be carried on the Procurement Program until another item or items are cancelled in order to provide sufficient funds for the item...

A third example of this tension appears in the minutes of the February 12, 1930 Procurement Board meeting:

The question of the procurement of 14 Amphibian airplanes, in the amount of $681,380.00 , set up and approved under 1930 funds, was presented. After discussion the Board, without objections, recommends that approximately 17 of the Loening Amphibians with "Wasp" engines be procured immediately from the funds set up. However, the exact number that can be procured from these funds will be determined after negotiations have been concluded.

These and numerous other similar discussions illustrate the extent to which the military procurement boards faced fixed budgets that induced trade-offs between various budget items. Increases in the cost of one item came either at the cost of a reduction in the quantity of that item, or a reduction somewhere else in the budget. The demand system used in our theory is meant to reflect, in a stylized way, these features.

The Procurement Board meeting minutes also reveal the extent to which the military had to negotiate prices with individual airframe manufacturers after the 1926 law changes (unfortunately very few records survive for the period before 1926). This feature shows up in the discussion of the Loening Amphibians discussed above. Another example, from the minutes of the Board's April 11, 1927 meeting describe how,

The question of procurement of 87 primary training planes, PT-1's for the Air Corps requirement was discussed, and the Board recommended contracts be placed with the Consolidated Aircraft Corporation, but not until such time that a satisfactory price could be obtained that would materially reduce unit cost.

Some military oversite was exercised to limit the potential profits that manufacturers could extract from an accepted design. A discussion of the purchase of Amphibious aircraft from Loening in the Board minutes of December 8, 1926, for example, describe how,

> *Prices for the Loening Amphibians are understood to be subject to negotiation, as to date the Leoning Aeronautical Engineering Corporation have not submitted figures justifying the price quoted of $23,500 per plane.*

Together these and other similar quotes suggest that, in the period after 1926, the military was clearly forced to negotiate with manufacturers over the prices of the aircraft produced under their designs. This monopolist-monopsonist bargaining is incorporated into our theory.

B.4 The aircraft industry in comparison countries

This appendix discusses the state of the airframe and aero-engine industries in the various comparison countries considered in our anlaysis. We begin with a brief overview of the comparison countries, before turning to a more detailed discussion of each individual market.

The United Kingdom was the most similar comparison country to the United States. The U.K. industry was composed of a large number of airframe producers and a smaller number of engine makers. Military orders made up the majority of the market, as they did in all countries during this period. While the government played an active role in the industry, there were no major policy changes around the time of the US policy change that we study that would affect our ability to use the British industry as a counterfactual.

For airframes, Japan also provides a useful comparison country. The airframe sector in Japan was somewhat more concentrated than in the United States or United Kingdom, and the industry was younger. As in other countries, the government was the primary source of demand, but, importantly, we have not identified any major policy changes that would cause problems for our study. The engine sector in Japan was not sufficiently developed to provide a valid comparison for that analysis.

We also use data from Germany and Italy in our analysis of engine technology. However, for airframes, restrictions imposed on Germany by the Treaty of Versailles limited production, so Germany is not included in the airframe analysis. We also considered including Italy and the Soviet Union in our analysis of airframe technologies, but in both cases there were too few designs in the early 1920s for these to serve as useful comparison countries.

We also collected data for France, and important aircraft producer during this period. However, in 1928 the French government made a substantial policy change aimed at spurring the introduction of new aircraft prototypes. Since this "prototype policy" corresponds fairly closely to the timing of the policy change in the United States that we study, France will not provide a clean comparison for our main analysis. Instead, in Appendix G we provide a separate analysis of the prototype policy. These results provide validation for our basic approach.

B.4.1 The aircraft industry in the United Kingdom

This appendix section describes the developments in the UK aircraft industry during the interwar period. The discussion below draws on Fearon (1969, 1974), Broadberry (1997), Edgerton (2013), and Kelly (2013).

The UK aircraft industry had a slow start. Private aviation was limited and the main source of demand prior to World War I. With the outbreak of war, production efforts shifted to military uses and, ultimately, the founding of the Air Ministry and Royal Air Force in 1917. By the end of the war, the UK was among the world leaders, if not in the lead, in terms of airpower (Fearon, 1974). After the war, the industry experienced a prolonged period of low demand, as it did elsewhere.

Disagreement exists over the dynamisms of the British aircraft industry in the inter-war period. Fearon (1974) suggests that the British industry was somewhat backward technologically during the inter-war period and only began delivering world-class aircraft under the pressures of rearmament. Edgerton (2013) disagrees and provides evidence that in fact the British industry was strongly supported by military demand and continued to produce innovative aircraft throughout the interwar period. Broadberry (1997) provides a useful review of this debate. The performance measures recorded in our data appear to be more in line with Edgerton's more positive view of the British industry during the inter-war period than the more pessimistic view of Fearon.

There is little debate over the central role that military demand played in the British industry. In the early 1920s, to maintain the industry, which was deemed vital to the national defense, the Air Ministry established a "ring system" of airframe (and aircraft engine) producers to fill a stream of procurement orders throughout the interwar period. The effect was to concentrate orders among a few firms and would remain financially viable.

In terms of industry structure, the UK industry shared many similarities to the U.S. industry. The industry was relatively unconcentrated, particularly airframe manufacturers. In 1920 the census records 13 active firms in the industry. This had risen to 38 by the 1930 census, but most of the production was concentrated in 16 large firms. These larger firms produced essentially all of the military orders.

Like the U.S., British government institutions were active in aeronautical research. The two main centers were the National Physical Laboratory (NPL) at Teddington and the Royal Aeronautical Establishment (RAE) at Farnborough. The NPL operated a wind tunnel and was active in aerodynamic testing, while the RAE was more focused on testing components such as engines and propellers.

B.4.2 The aircraft industry in Japan

This appendix provides a brief overview of the Japanese aircraft industry, drawn largely from Mikesh and Abe (1990). The major Japanese aircraft producers, Mitsubishi, Kawasaki and Nakajima, entered the industry during the First World War. Mitsubishi and Kawasaki were part of larger industrial conglomerates, while Nakajima was an independent company from the beginning. Following the war, Japan turned to its French and British allies for help in developing its military air capabilities. A French delegation in 1919 trained pilots for the Japanese Army and introduced French Breguet, Salmson, Nieuport, Caudron and SPAD aircraft. Japanese Naval aviators were trained by a British delegation, which arrived in 1921. The brought with them British aircraft from Avro, Short, Gloster, Sopwith, Blackburn and Supermarine. Additional European engineers also arrived to help the fledgling industry, while Japanese technical missions visited Germany, England, France and the U.S. But early on there was a clear interest in producing new Japanese designs, as evidenced by the opening of the first wind tunnel in Japan in 1921.

During the 1920s, Japanese firms produced a mix of European airframes and original Japanese designs. New designs came both from private aircraft producers as well as government research facilities. Since aero-engines were more difficult to produce than airframes, early Japanese aircraft were often powered by imported engines or engines built on license. For example, Kawasaki produced engines using a licensed BMW design. One consequence of this pattern is that we are unable to include Japan in our analysis of innovation patterns in engines. In 1930, the Japanese Army and Navy decided that they would, henceforth, purchase only airframes and engines based on Japanese designs, though the country continued technical missions in order to learn from foreign producers.

Throughout the inter-war period, the Japanese aircraft industry, and particularly the production of military aircraft, was dominated by three companies: Mitsubishi, Kawasaki and Nakajima. Thus, the industry structure remained essentially stable through the period we study, though there was some entry by smaller firms.

B.4.3 The aircraft industry in France

This appendix provides background information on the French aircraft industry during the inter-war period. This discussion draws heavily on Chapman (1991) as well as Higham (2003).

At the close of the First World War, the French aircraft industry was world-class and the French military air arm was the largest in the world. Despite this initial lead, the relative decline of the French industry in the inter-war period set the stage for the rapid defeat of French air power in the Second World War. The French aircraft industry rapidly contracted after the war, shrinking from around 200,000 workers near the end of the war to just 5,200 in 1920 Chapman (1991). Chapman reports that by the late 1920s, there were 23 companies producing airframes in France and around 10 aero engine producers. Of these, a small number of airframe producers were internationally competitive, including Bréguet, Potez, Farman and Lioré et Olivier, as well as the two major aero engine producers, Hispano-Suiza and Gnôme-Rhône.

The French industry remained highly reliant on military orders in the 1920s. To keep firms alive, in the 1920s the government followed a policy of sharing aircraft orders among manufacturers, similar to the approach pursued in the U.K. This helped firms survive, but it meant that production orders were small. As a consequence, it has been argued that French firms failed to adopt modern mass production methods, continuing to rely instead on craft production to fulfill the small number of orders they received.

French policy underwent a substantial change in 1928 in response to the industry's perceived relative decline. The government created a new Air Ministry to manage the industry. The Air Ministry set out with the goals of increasing innovation, decentralizing production away from the Paris region (in part for defensive reasons), and rationalize and concentrate the industry. The new policies related to research are particularly relevant for our purposes. From 1928-1932, the central element of the Air Ministry's support for innovation was a prototype policy. Under this policy, firms that developed new prototypes were reimbursed 80% of the cost, regardless of the utility of the new design. In addition, the state offered bonuses for advances that increased speed or climb rate. However, in exchange aircraft manufactures were required to hand over all patent and licensing rights to the state. Chapman (1991) reports that the prototype policy motivated a surge in innovation in new designs between 1929 and 1932, but that many of the new designs had little value.

Another aspect of the 1928 policy changes that is relevant for this study is the Air Ministry's effort to encourage firms to merge and rationalize their operations. This policy led to two mergers between airframe producers, one between Loire and Nieuport and a second between Potez and CAMS. It also led to the organization of *groupements*, collections of firms that pooled some risk and financial resources but with separate administration and production. One of these, the Société Generale Aéronautique, combined Hanriot, Amoit-SECM, Loire-Nieuport, the Société Aérienne Bordelaise and the engine builder Lorraine. The second, Groupement Aéronautique Industriel included Bréguet, Lioré et Olivier, Potez, and the engine-makers Hispano-Suiza and Renault. However, Chapman suggests that rather than leading to the rationalization of production, these groups merely represented "phony mergers" that mainly served to pool risk and share financial resources across firms. In practice, individual manufacturers stubbornly resisted the halfhearted pressure of the government for consolidation.

One consequence of the 1928 policies is that we cannot use France as a comparison country. If anything, we would expect investments in research to have stimulated performance improvements by French airframe makers. If France is included among our control group in the airframe analysis, this will result in a downward bias in estimates of the rate of airframe performance growth in the U.S. Also, the fact that the Air Ministry was pushing for mergers in the late 1920s makes merger activity in France a less attractive point of comparison for the merger activity that we observe in the U.S. during that period.

The formation of a new government under Edouard Daladier in 1933 prompted a new but short-lived round of reform in the aircraft industry. The new head of the Air Ministry, Pierre Cot, won more independence for the air arm of the military, continued to push firms to concentrate, and was able to gain approval for a program of military aircraft purchase called Plan I. Military procurement policies were adjusted so that manufacturers received reimbursement only for viable prototypes and production was reoriented towards fewer larger firms. However, political instability weakened the Air Ministries ability to push through reforms in the years from 1932-36. As a result, relatively little true reform occurred during this period.r

The inability of the industry to reform itself, together with underlying political forces, led eventually to the nationalization of the French aircraft industry in 1936. Following nationalization, the Air Ministry reorganized roughly 80% of the industry (Chapman, 1991, p. 106) into five large companies organized along regional lines. Given the enormity of this change, our analysis does not use French data after nationalization.

B.5 NACA

This section presents additional background information on the National Advisory Committee on Aeronautics (NACA), which relies on Bilstein (1989). NACA was founded in 1915, during WWI, by an act of Congress. NACA was modeled after aeronautical research centers in Europe, particularly those in France and Britain. Its focus was on basic research, while the more applied problems of testing and improving aircraft were left to the Army and Navy.

In the early 1920s NACA employed a number of research engineers working at the Langley airfield in Virginia. Bilstein (1989) reports that 100 workers were employed in 1925. At Langley, NACA constructed a small variable density wind tunnel that began operations in 1922. By 1925, the Langley operation also included an experimental engine laboratory a well as 19 aircraft dedicated to test flights. A propeller research tunnel went into service in 1927, followed by a full-scale wind tunnel in 1931.

Figure B2 describes the NACA budget across the study period using data collected from the NACA Annual Reports for 1922-1936. The budget grew fairly slowly across the early 1920s and then increased substantially starting in 1930. The high level of expenditure in 1930-31 reflects the cost of constructing the new wind tunnel that opened in 1931. Given these patterns, increased spending on research by NACA seems unlikely to explain the change in the rate of airframe performance increase that we observe starting in 1926. This is not to say that NACA did not generate important inventions. It did, including the NACA cowling for reducing the drag on air-cooled engines, introduced in 1928, and a system of airfoil classifications. However, these innovations were publicly available for use by both U.S. and foreign airframe producers. For example, the new cowling developed by NACA in the late 1920s was both described in a published technical note as well as in an article in *Aviation* magazine (Rowland, 1985). Moreover, similar research was being undertaken by NACAs foreign counterparts.

B.6 Market shares of engine producers

Figure B3 shows the market share of different military engines producers between 1919 and 1939. Panels A and B show the share of total output and the share of total horsepower, respectively.

Figure B2: NACA budget during the study period

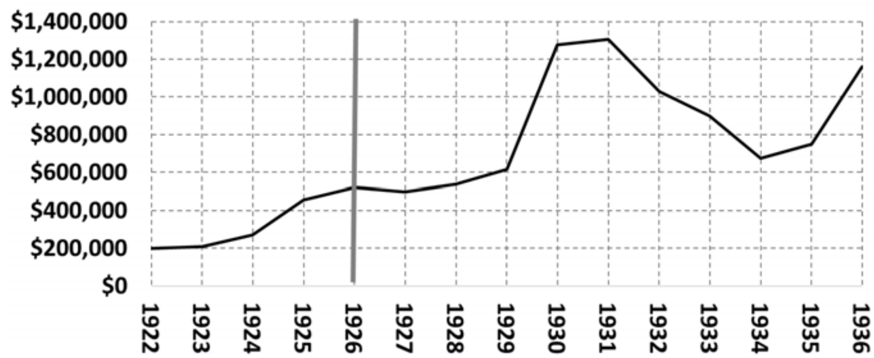
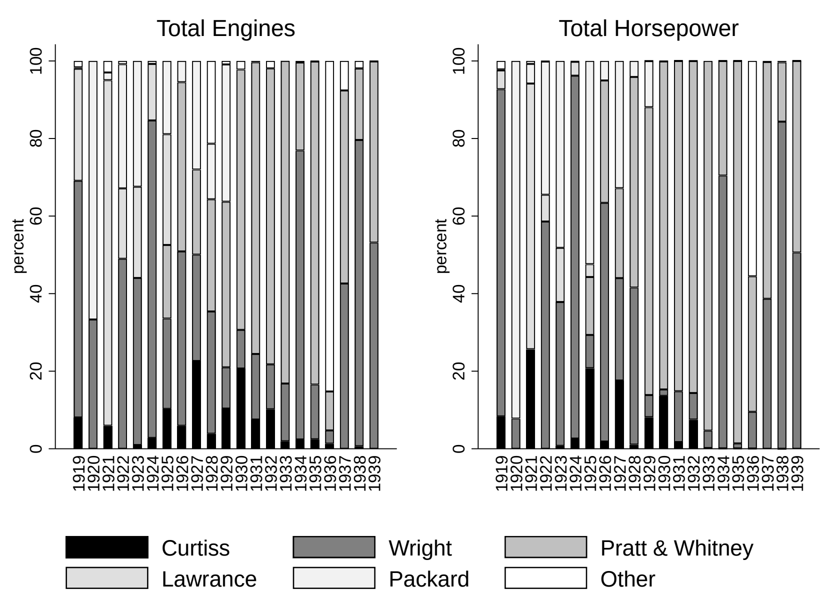


Figure B3: Military Engine Producer Market Share



C Data Appendix

U.S. military aircraft data

Swanborough, Gordon and Bowers, Peter M. (1963). *United States Military Aircraft Since 1908.* London: Putnam & Company Ltd.

Swanborough, Gordon and Bowers, Peter M. (1968). *United States Navy Aircraft Since 1911.* New York: Funk & Wagnalls.

Fahey, James C. (1946). *U.S. Army Aircraft 1908-1946.* First edition. New York: Ships and Aircraft.

U.K. military aircraft data

Thetford, Owen. (1988). *Aircraft of the Royal Air Force Since 1918.* Eighth edition. London: Guild Publishing.

Thetford, Owen. (1991). *British Naval Aircraft Since 1912.* Sixth revised edition. Annapolis: Naval Institute Press.

French military aircraft data

Jane, Frederick. *All the World Aircraft.* 1919-1920, 1922-1929. London: Sampson Low, Marson & Co. (not published in 1921)

Jane's All the World Aircraft. 1930-1938. London: Sampson Low, Marston & Co.

Japanese military aircraft data

Mikesh, RC and Abe, S. (1990). *Japanese Aircraft 1910-1941.* London: Putnam Aeronautical Books.

German fighter data for predicted performance figure

Kosin, Rudiger (1988). *The German Fighter Since 1915.* London: Conway Maritime Press Ltd.

Engine data

General: Gunston, Bill (1995). *World Encyclopedia of Aero Engines.* Third edition. Sparkford, U.K.: Patrick Stephens Limited.

US: Fahey, James C. (1946). *U.S. Army Aircraft 1908-1946.* First edition. New York: Ships and Aircraft.

UK: Lumsden, Alec (1994). *British Piston Aero-Engine and their Aircraft.* Shrewsbury, U.K.: Airlife Publishing Ltd.

France, Germany and Italy:

Jane, Frederick. *All the World Aircraft.* 1919-1920, 1922-1929. London: Sampson Low, Marson & Co. (not published in 1921)

Jane's All the World Aircraft. 1930-1938. London: Sampson Low, Marston & Co.

D Innovation timing and funding type for key designs

This appendix provides some supporting information for statements made in the main text about how the development of new designs were funded and how long it took for new designs to be developed. We focus on the most important U.S. fighter and bomber designs produced during the study period using data from Gordon Swanborough and Peter M. Bowers (1963) *United States Military Aircraft Since 1908.*, London: Putnam & Company Ltd. and Gordon Swanborough and Peter M. Bowers (1968) *United States Navy Aircraft Since 1911.*, New York: Funk & Wagnalls. These sources often describe the way that new designs were funded (e.g., private venture, joint project, government contract). In addition, they also provide information on when the project was started, when the design first flew, and when the first production contract was issued. These dates are useful for thinking about the kind of delays we might expect in the innovation process.

Table D1 reports the data. Note that this list is smaller than the list of new designs used in our main analysis. To keep things manageable, we have included only major original designs in this table. The table does not include less important designs nor does it include the many evolutionary improvements that were made in newer versions of existing designs. The information on funding shows that a large number of the key designs produced during the interwar period were private ventures, particularly designs intended for the Army Air Corp. The Navy was much more likely to issue contracts for the development of prototypes. There is no evidence that the form of funding changed substantially across the study period. The information on timing suggests that most new designs were produced within one to two years, and that production contracts usually came within 2-3 years of project initiation. This suggests that the timing of the response indicated in our main analysis is reasonable.

Table D1: Information on key U.S. fighter and bomber designs

	Aircraft	Type	Development type	Began	First flown	Production version ordered
Boeing						
	PW-9/FB	Fighter	Private venture	?	April, 1923	September, 1924
	F2B	Fighter	Private venture	?	Nov., 1926	March, 1927
	P-12/F4B	Fighter	Private venture	1928	June, 1928	June, 1929
	P-26	Fighter	Joint with Army	1931	March, 1932	January, 1933
	B-9	Bomber	Private venture	1930	April, 1931	Not ordered
	B-17	Bomber	Army competition	1934	July, 1935	June, 1939
Brewster						
	F2A	Fighter	Navy contract	1936	Dec., 1937	June, 1938
Curtiss						
	18-T	Fighter	Navy contract	1918	July, 1918	Not ordered
	CS	Bomber*	?		1923	?
	PW-8	Fighter	Private venture	1922	May, 1923	September, 1923
	P-1/F6C	Fighter				March, 1925
	F8C	Fighter	Army competition	1924		June, 1927
	F11C	Fighter	Navy contract	1932	June, 1932	October, 1932
	P-36	Fighter	Privately financed	1934	Nov., 1934	July, 1937
Douglas						
	DT	Bomber	?	1921		1921
	B-18	Bomber	Privately financed	1934	?	January, 1936
	TBD	Bomber	Navy contract	1934	April, 1935	February, 1936
Great Lakes						
	BG-1	Bomber	Navy contract	1932	1933	November, 1933
Grumman						
	FF/SF	Fighter	Navy contract	?	1931	?
	F2F	Fighter	Navy contract	1932	October, 1933	?
	F4F	Fighter	Navy competition	1935	September, 1937	June, 1938
Huff-Daland/Keystone						
	LBS	Bomber	?	1923	1923	1927
Martin						
	MB-2	Bomber	?	?	?	1920
	BM	Bomber	Navy contract	1928	1930	April, 1931
	B-10	Bomber	Private venture		March, 1932	January, 1933
Nothrop						
	BT/A-17	Bomber	From civil design	?	1935	?
Seversky						
	P-35	Fighter	Private venture	?	1935	1936
Thomas-Morse						
	MB-3	Bomber	Army contract	1918	February, 1919	1919
Vought						
	VE-7	Fighter	?	?	1918	?
	SBU	Bomber	Navy contract	1932	May, 1933	January, 1935
	SB2U	Bomber	Navy contract	1934	January, 1936	October, 1936
	F4U	Fighter	Navy contract	1938	May, 1940	June, 1941

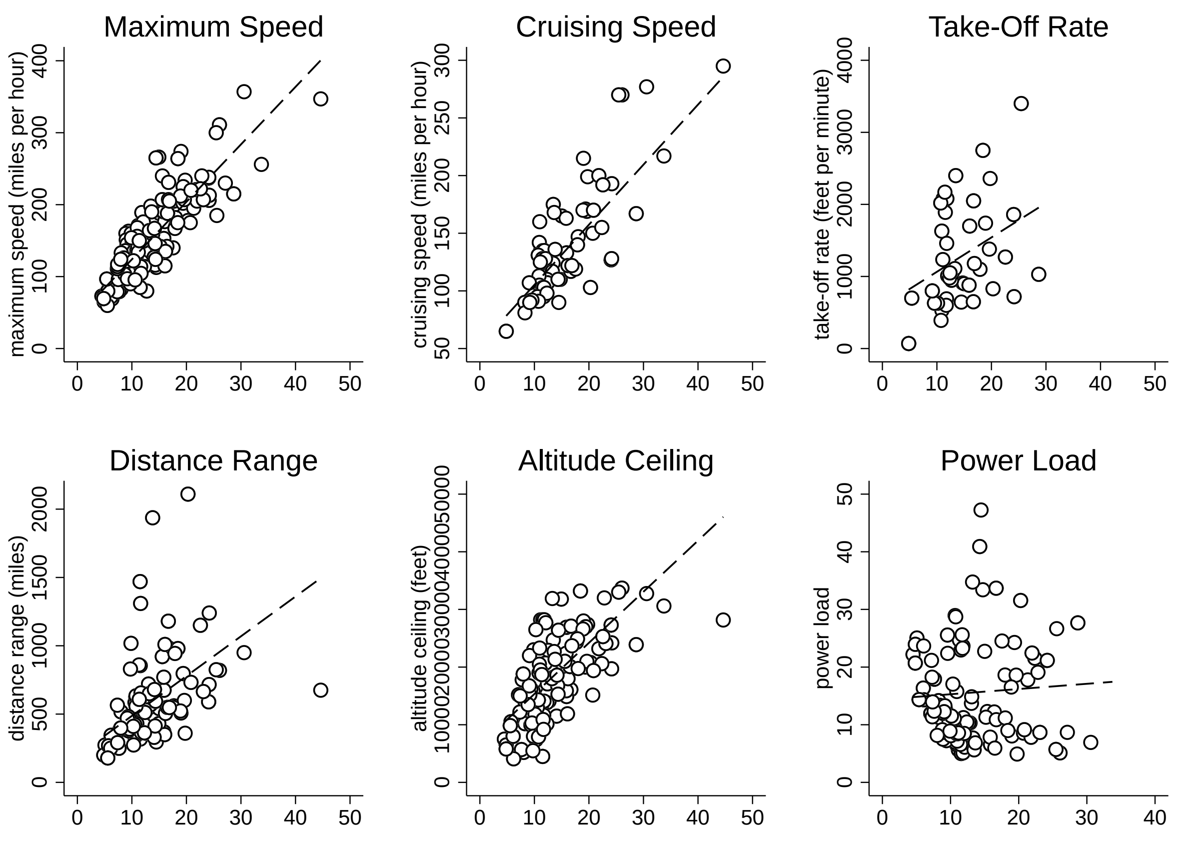
* Torpedo bomber

E Results Appendix

E.1 Relationship between airframe performance measures

The figure below illustrates the relationship between wing load and alternative measures of airframe performance. In each case, the correlation between wing load and the alternative measure is quite strong.

Figure E1: Correlation between AlternativeAirframe Performance Measures



Notes: Each panel shows the relationship between wing load and the given alternative measure of airframe performance for the US airframe industry.

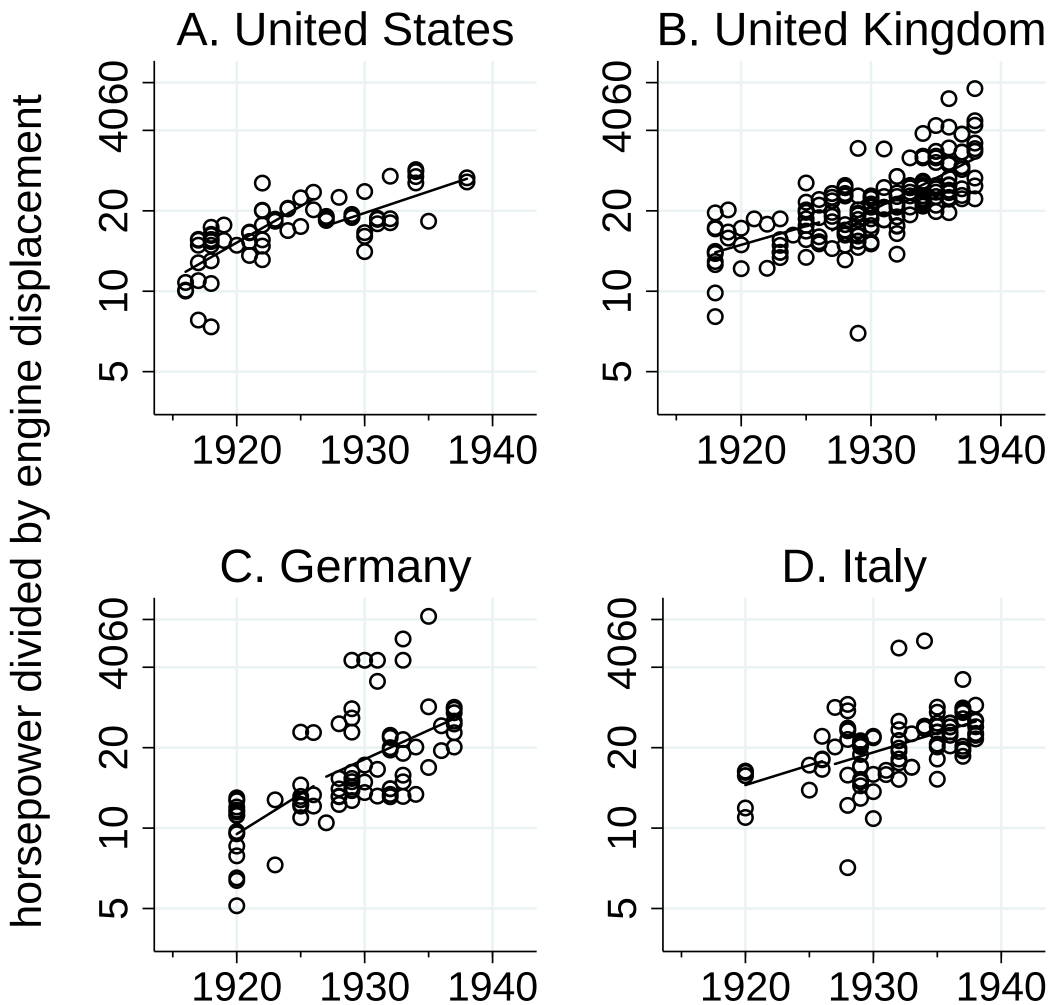
E.2 Comparison of airframes and engine by country

The figures below plot technological progress in airframes (fighters) and engines over time. Figure E2 compares airframes in the United States, United Kingdom, and Japan. Figure E3 compares airframes in the United States, United Kingdom, Germany, and Italy.

Figure E2: Airframe Comparison by Country

Notes: Each panel plots wing load over time for the United States (Panel A), United Kingdom (Panel B), and Japan (Panel C).

Figure E3: Engine Comparison by Country



Notes: Each panel plots horsepower divided by piston displacement over time for the United States (Panel A), United Kingdom (Panel B), Germany (Panel C), and Italy (Panel D)

E.3 Additional results for airframes

In the analysis of airframe innovation presented in the main text we focus on wing load as the dependent variable and the market segment for fighters. For fighters there is clear connection between wing load and the characteristics demanded by military procurement. In the table below, we replicate the result from the main text for wing load in column 1 and show that the pattern also exists when we use the maximum speed as the dependent variable in Column 2. In Column 3, we use the first principle component of wing load, maximum speed, and power load together with the climb rate and cruising speed after applying multiple imputation as the dependent variable.[45] The results are similar. The remaining columns confirm that we obtain a similar pattern of results for bombers (columns 4 through 6) and reconnaissance (columns 7 through 9).

[45]Since we do not observe each performance measure for all new designs we use multiple imputation to impute missing data assuming a multivariate normal distribution. We use the `mi impute mvn` command in `Stata`©.

Table E1: Robustness Results for Airframe Innovation in the United States Before and After 1926

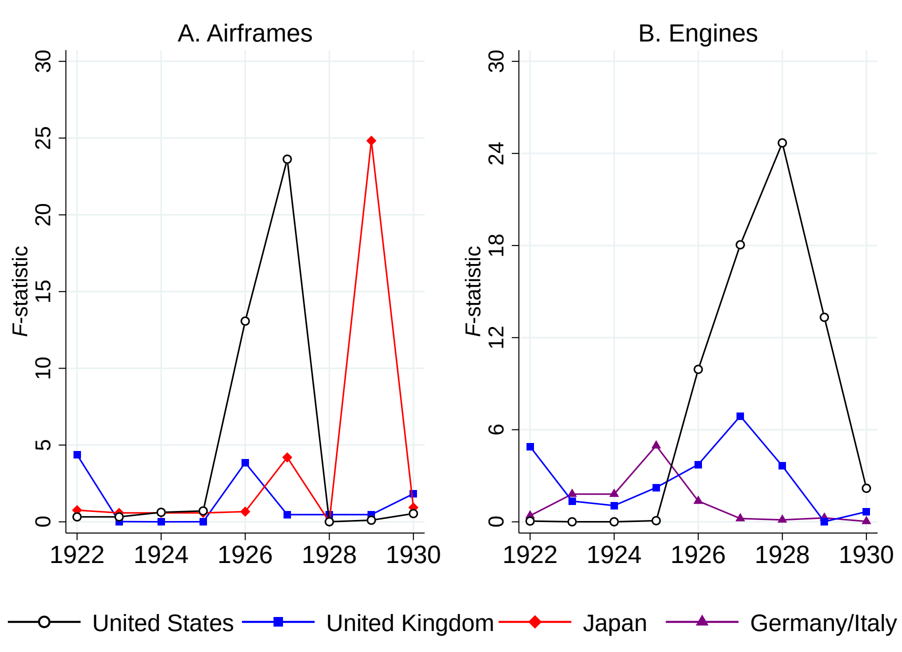
	Fighters			Bombers			Reconaissance		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9
Outcome	Wing	Max	First	Wing	Max	First	Wing	Max	First
(in log)	Load	Speed	PCA	Load	Speed	PCA	Load	Speed	PCA
Before 1926 × year × US	-0.023	0.002	0.026	0.012	0.001	0.002	-0.014	-0.004	0.009
	(0.010)	(0.004)	(0.034)	(0.001)	(0.008)	(0.006)	(0.009)	(0.006)	(0.010)
After 1926 × year × US	0.044	0.048	0.125	0.070	0.049	0.030	0.006	0.020	0.038
	(0.021)	(0.013)	(0.020)	(0.023)	(0.018)	(0.004)	(0.012)	(0.010)	(0.014)
weighted by output	yes	yes	yes	yes	yes	yes	yes	yes	yes
F-statistic	8.3	11.4	6.3	6.1	6.1	13.5	1.8	4.4	2.9
p-value	0.006	0.001	0.012	0.018	0.018	0.000	0.184	0.041	0.089
observations	155	199	281	90	136	191	127	196	284

Notes: The table presents results from estimating equation (9) comparing the United States to the United Kingdom and Japan. All specifications use new designs from 1916 to 1938 for each country and control for the level of airframe innovation in each country as well as a year fixed effects. Columns 1 through 3 show results for fighter airframes, columns 4 through 6 show results for bomber airframes, and columns 7 through 9 show results for reconaissance airframes. The dependent variable is given at the top of each column. In columns 3, 6, and 9, the dependent variable is the first principle component of the log of wing load, maximum speed, power load, climb rate, and cruising speed after applying multiple imputation. The number of observations in columns In columns 3, 6, and 9 corresponds to the number of unique airframe designs. In each column the reported F-statistic and p-value are for the null hypothesis that the estimated coefficients for the rate of technological progress before and after 1926 are equal. Standard errors are clustered at the country-year level.

E.4 Additional results for airframe and engine "placebo"

The figure below shows the results of allowing the "treatment year" to change for each country separately for both airframes (Panel A) and engines (Panel B). In Panel A, the results for airframes indicate a sharp jump after 1926 and reaching a peak in 1927 for the United States and no similar change for the United Kingdom. The jump for Japan in 1929 suggests a change in the rate of innovation around this period. However, results for comparisons between the United States and other countries presented in the main text indicate that innovation in the United States was *faster* than in the other countries. In Panel B, the results for engines show a more gradual with the F-statistic reaching the largest value in 1928 for the United States, but staying otherwise relatively constant for the United Kingdom and Axis countries.

Figure E4: Placebo for Airframe and Aircraft Engine "Treatment Year" by Country



Notes: Each panel reports the F-statistic based on the null hypothesis for the equality of α_{before} and α_{after} coefficients from a version of equation (8) for each country separatley and for an assumed break year between 1922 and 1930. Panel A shows the results for airframes using the log of wing load as the dependent variables. Panel B shows the results for aero-engines using the log of horsepower divided by displacement as the dependent variable. Standard errors are heteroskedasticity robust.

E.5 Additional results for individual firms

This subsection presents performance patterns at the level of individual producers for three of the most important airframe firms during this period, Boeing, Curtiss and Douglas. These graphs cover all of the aircraft produced for the military by each of these three firms during the study period. The data come from different sources than those used in the main analysis, so these results also provide a check on our main data.[46]

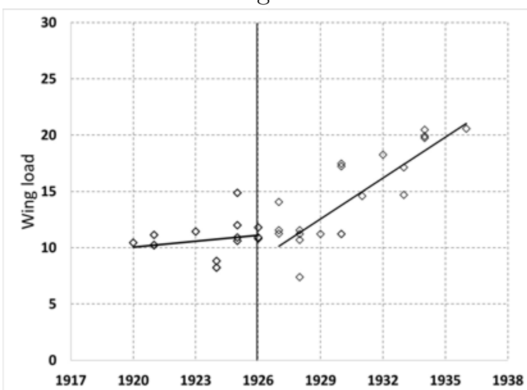
These figures indicate that the same pattern of accelerated innovation after 1926 documented in the main analysis also appear when we look at performance measures by company. The only exception here is for the maximum speed of Curtiss aircraft. It is worth noting that these figures include all types of military aircraft, so the changes in performance may also be influenced by shifts in the mix of aircraft being produced. Because of this, we view these as somewhat less indicative of overall performance improvements than the results shown in the main text, which focus on specific aircraft types. Nevertheless, the fact that we view similar patterns within companies provides further support for the results presented in the main text.

[46]The data for Boeing come from Bowers (1989). The Curtiss data are from Bowers (1987). The Douglas data are from Francillon (1988).

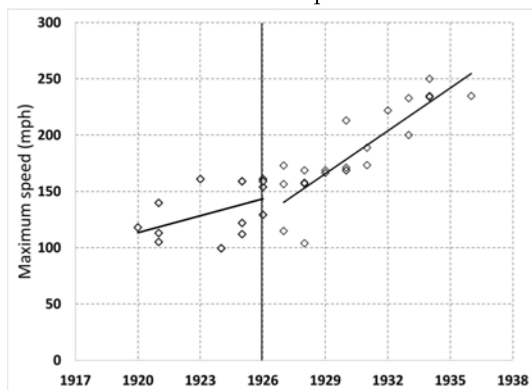
Figure E5: Evolution of aircraft performance by company

Boeing Aircraft

Wing load

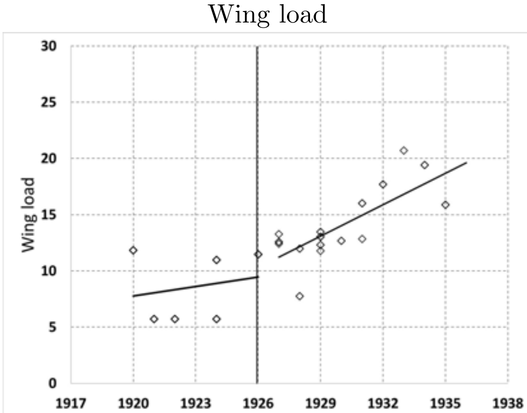


Maximum speed

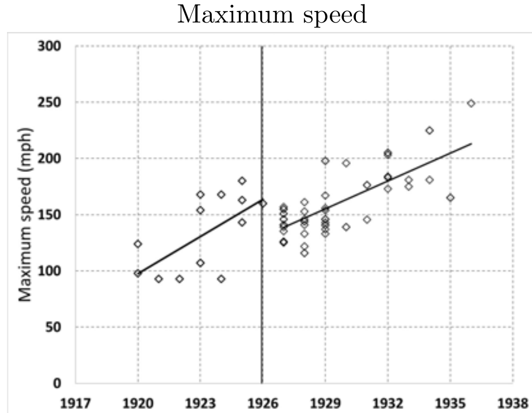


Curtiss Aircraft

Wing load

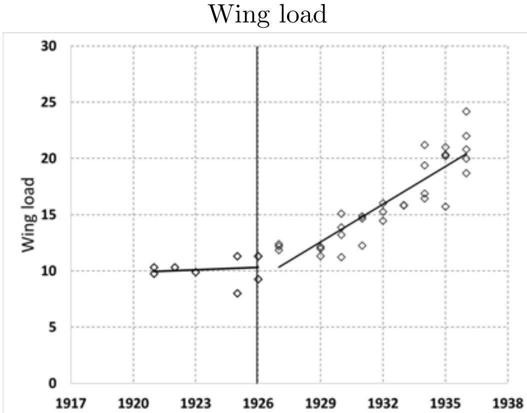


Maximum speed

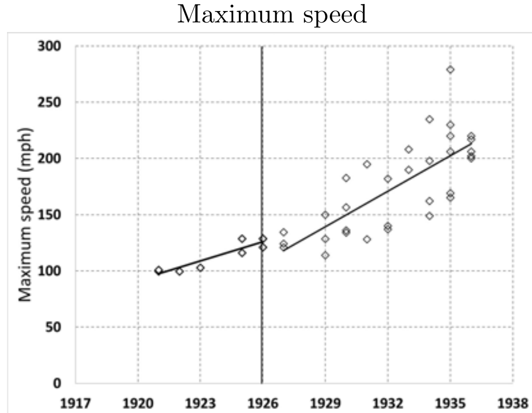


Douglas Aircraft

Wing load



Maximum speed



E.6 Comparing innovation in military and civil designs

In this appendix we compare innovation patterns in the U.S. for firms focused on the military market and those focused instead on the civil/commercial market. This is a useful comparison because it can shed light on which of these two sides of the market appears to have been driving innovation forward in the period after 1926. If the key force at work after 1926 was changes in the attractiveness of the civil/commercial market due to policy changes such as the Air Commerce Act, then we should expect firms focused entirely on that market to innovate at least as fast, if not faster, after 1926, than firms focused mainly on selling to the military. In contrast, if the change in military procurement policy that we highlight was more important, then we should expect faster innovation among producers focused on the military market.

For airframe producers, we study all designs from the six largest U.S. airframe producers. We focus in particular on a comparison between those producers focused primarily on the military market (Boeing, Curtiss, Douglas and Martin) and those focused primarily on the civil/commercial market (Fairchild and Lockheed).[47] There are two important points to note about the airframe analysis. First, we focus on whether firms were focused on the military or civil market here, rather than whether particular designs were intended for military or civil use, because expect there to be some spillovers between military and civil designs within a firm. Second, we study patterns only after 1926. This is because we observe too few designs from the major civil producers before 1926 to conduct a pre/post analysis.

For aero-engines, we focus on the designs produced by all firms, comparing the main producers of military engines (Wright, Curtiss and Pratt & Whitney) to all other firms. These data come from volumes of Jane's *All the Worlds Aircraft* and cover all major new engine designs. Since these data cover all firms, we do have enough civil designs to study relative patterns both before and after 1926.

As a starting point for this analysis, Figure E6 compares innovation patterns after 1926 among firms focused mainly on the military market and those focused mainly on the civil market. Consistent with the qualitative narrative presented in the main text, this figure shows that firms focused on the civil market were producing more advanced designs in 1926, but that firms focused on the military market innovated more rapidly after 1926 so that by the mid-1930s these firms were producing the most advanced designs, in terms of both wing load and maximum speed.

Table E2 presents regression results quantifying the difference between the military and civilian markets for airframes and engines shown in Figure E6. Columns 1 and 2 estimate the difference in slopes depicted in panels A and B, while column 3 quantifies the difference shown in panel C. Finally, column 4 compares relative performance of military and civilian engines before and after 1926; innovation was slower for military engines before 1926 and

[47] See Appendix E.5 for details on these data.

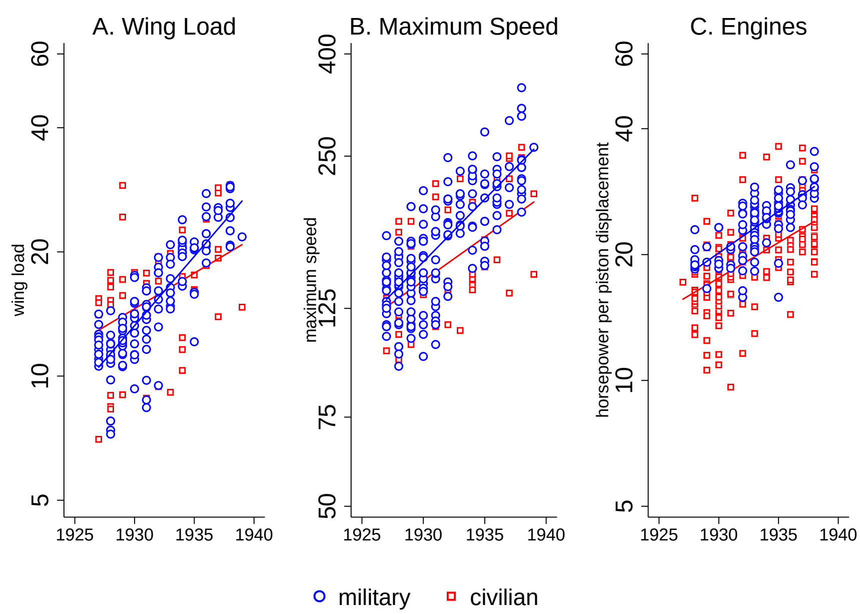
accelerated afterward. Taken together, the results suggest limited scope for the results presented in Section 5 to be driven by changes in the civilian market, rather than the change in IP protection that is the main focus of this paper.

Table E2: Regressions Comparing Military versus Civil Airframe and Engine Producers

Outcome (in log)	(1) Wing Load	(2) Maximum Speed	(3) HP per displacement	(4) HP per displacement
After 1926 × military × year	0.038	0.028	0.021	0.022
	(0.015)	(0.008)	(0.011)	(0.010)
Before 1926 × military × year				-0.050
				(0.021)
firm fixed effects	yes	yes	yes	yes
year fixed effects	yes	yes	yes	yes
observations	225	261	270	326

Notes: The dependent variables in columns 1 and 2 are the log of wing load and the log of maximum speed, respectively. The dependent variable in columns 3 and 4 is the log of horsepower per piston displacement. All specificatitons include firm and year fixed effects. Standard errors are clustered at the year level.

Figure E6: Comparison of Military and Civil Airframes and Engines After 1926



Notes: This figure shows the pace of technological progress in airframes measured using wing load (Panel A) and maximum speed (Panel B) and in engines measured using horsepower per piston displacement (Panel C) for the military and civilian markets.

F Merger Appendix

Figure F1 describes the pattern of entry, exit and merger activity among US aero-engine producers. These producers can be roughly divided into integrated aero-engine and air-frame firms (such as Aeromarine, Curtiss, Kinner), firms affiliated with major automotive manufactures (Allison, Continental, Lycoming, Packard), independent firms, and the major military engine producers (Wright and Pratt & Whitney). Lawrence, which also made military aircraft engines, was absorbed by Wright early in the 1920s. This loss of an independent producer was part of the impetus for the Navy to encourage the founding of Pratt & Whitney by former Wright employees, which aimed at maintaining some competition in the market. Curtiss really belongs among both the integrated firms and the military engine producers, since it produced military engines before the merger with Wright. Subsequent to the merger, engine production activities were concentrated in the Wright division of Curtiss-Wright. It is worth noting that two of the integrated firms, Kinner and Aeronca, do not appear in Figure 3 because they primarily produced small light planes for the civil market.

These data show that the only substantial vertical-complement merger activity between 1920 and 1934 occurred among the military engine producers. All of the integrated firms remained integrated during the study period, while all of the other firms remained focused only on engine production.

The next set of data, described in Figure F2, shows merger patterns among British airframe and aero-engine producers. We can see that British firms did not undertake the same type of merger activity between airframe and aero-engine producers in the late 1920s observed in the U.S. The only substantial merger during this period was the purchase of the airframe producer Avro by the integrated group that already included Armstrong-Whitworth Aircraft together with Armstrong-Siddeley Engines. This grouping was itself a byproduct of the mega-merger between two enormous armament firms, Vickers and Armstrong Whitworth, which took place in 1927. That merger resulted in the spin-off of the aircraft and aero-engine holdings of Armstrong Whitworth as two separate companies both under the direction of Sir John Siddeley, who then used the opportunity to purchase Avro. The impetus behind this activity was thus driven by forces outside of the aircraft industry, which was of relatively little importance to the larger Armstrong or Vickers conglomerates.

Most importantly, we see no evidence that leading military aero-engine makers, such as Rolls-Royce, engaged in merger activity similar to what we have observed among U.S. aero-engine producers. Overall the pattern observed in Britain indicates that the pattern observed among U.S. producers were not being driven by broader industry trends, such as changes in technologies or production methods.

Figure F1: Entry, Exit, and Mergers, Among U.S. Aero-Engine Producers

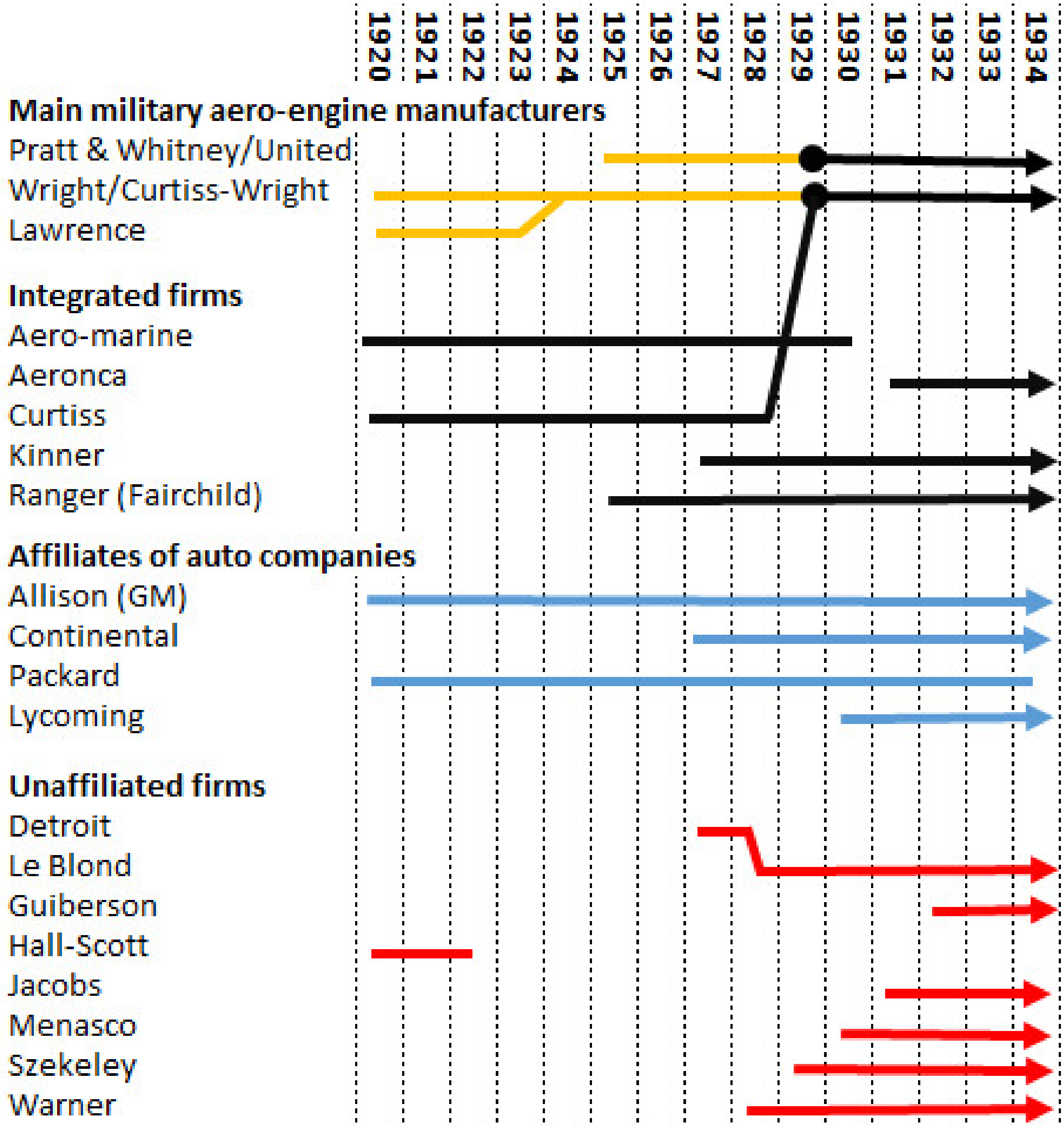
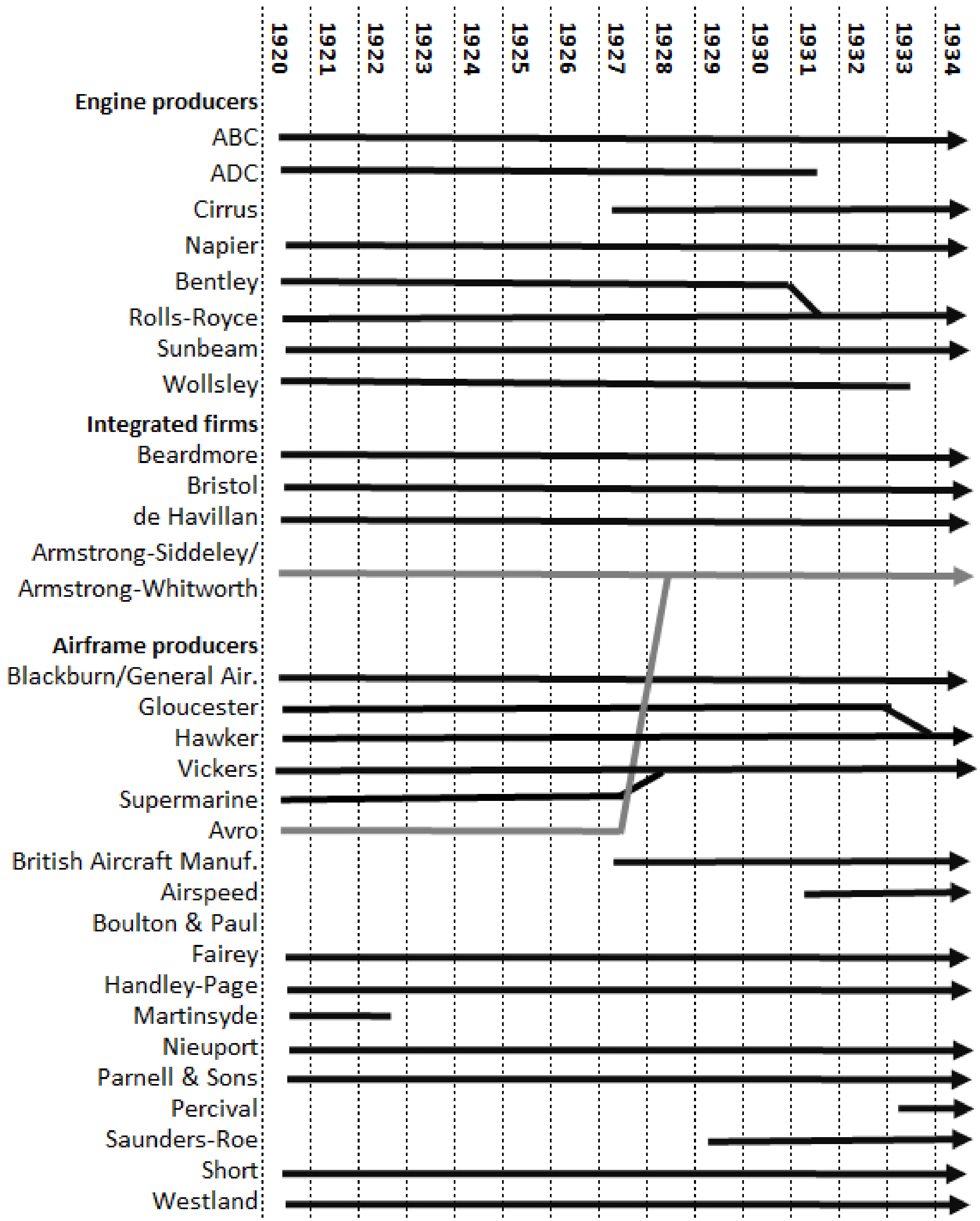


Figure F2: Entry, Exit, and Mergers, Among British Firms



G Evidence from the French "prototype policy"

It is also interesting to consider the effects of the French prototype policy of 1928. This is another policy that we would expect to have a positive impact on innovation (in our model it would roughly correspond to an increase in the fixed fee G paid for the production of a successful new design). Thus, studying whether this policy had the expected effects on innovation can provide an additional way to validate our data and methods.

The prototype policy was introduced by the head of the Aviation Ministry, Albert Caquot, to reverse the perceived decline of French aviation innovation relative to other countries. The policy encouraged the creation of new designs with improved performance, such as higher speeds, and paid 80% of the development cost of successful projects. Most of these rewards went to airframe designers, but a portion also went to aero-engine manufacturers.

The evidence in Table G1 is somewhat mixed. There is clear evidence of an acceleration in performance after 1928, relative to before, when we look only at the time-series for France. When comparing to other countries the evidence is weaker, but may suggest that the prototype policy enabled France to match or outpace improvements in airframes and aero-engines relative to other countries. However, it is worth noting that there is also evidence that this policy had some downsides. While it led to a proliferation of new designs, it did not provide these incentives through production contracts. As a result, French firms had little incentive to build planes that could be easily produced in quantity, nor did they gain experience with the kind of long production runs that firms needed in order to become more efficient at production.

Table G1: Results for Airframe and Engine Innovation in France Before and After 1928

A. France only

	The dependent variable is the log of:				
	Maximum Speed		Wing Load		HP per disp
	Fighter	Bomber	Fighter	Bomber	Engines
	(1)	(2)	(3)	(4)	(5)
Before 1928 × year × FR	0.010	0.027	0.054	0.024	0.020
	(0.007)	(0.005)	(0.006)	(0.004)	(0.005)
After 1928 × year × FR	0.086	0.098	0.062	0.064	0.049
	(0.015)	(0.009)	(0.018)	(0.026)	(0.009)
F-statistic	21.9	47.3	0.2	2.3	8.5
p-value	0.000	0.000	0.649	0.149	0.010
observations	90	66	97	59	206

B. Comparison between France and other countries

	The dependent variable is the log of:				
	Maximum Speed		Wing Load		HP per disp
	Fighter	Bomber	Fighter	Bomber	Engines
	(1)	(2)	(3)	(4)	(5)
Before 1928 × year × FR	-0.003	0.024	0.018	-0.005	-0.014
	(0.012)	(0.012)	(0.009)	(0.019)	(0.007)
After 1928 × year × FR	-0.002	0.024	0.018	-0.005	-0.014
	(0.012)	(0.012)	(0.009)	(0.019)	(0.007)
F-statistic	7.5	4.6	0.2	0.2	3.3
p-value	0.009	0.038	0.630	0.660	0.075
observations	183	124	185	112	493

Notes: Panels A reports the results for estimating a version of equation (8) for airframes in columns 1 through 4 and airfraft engines in column 5 for France. Standard errors are clustered by year. Panels B reports the results for estimating a version of equation (9) for airframes in columns 1 through 4 comparing France to the United Kingdom and Japan, and aircraft engines in column 5 comparing France to the United Kingdom, Germany, and Italy. Standard errors are clustered at the country-year level. In each panel, the dependent variable is the log of maximum speed (columns 1 and 2), wing load (columns 3 and 4), and horsepower per displacement (column 5).