Technological Opportunity and the Locus of Innovation: Airmail, Aircraft, and Local Capabilities[1]

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Abstract

This paper explores how innovation is jointly shaped by exposure to technological opportunities and local capabilities. We exploit a quasi-natural experiment, the establishment of the United States Post Office's Airmail routes, to analyze how a new technological opportunity spurred innovations in aircraft technology between 1915 and 1935. Using a novel dataset of historical patents, we find that the introduction of an airmail route into a county results in a 93% increase in aircraft-related patents in that county, on average. We also explore the role of local capabilities and find that different types of local knowledge have a heterogeneous effect on patent quality. We find that treated areas with more users and tinkerers produce more low-quality patents, whereas treated areas with more specialists and workers with higher education produce more high-quality patents. This research contributes to existing literature by refining our understanding of how technological opportunities lead to advances in early-stage technologies.

INTRODUCTION

Technology and innovation boost economic growth (Solow, 1957; Romer, 1990; King and Levine, 1993). So, in order to drive economic growth, national and regional economic policymakers often seek to put in place policies to enhance technological innovation by providing the private sector with R&D inputs, such as government funding for basic research (Bush, 1945; Salter and Martin, 2001) and small business grants (Howell, 2017). Existing research has primarily focused on such role of government in the upstream segment of the R&D value chain, namely governmental provision of R&D *inputs* to the private sector, with comparatively less focus on spillovers derived from government activities in the downstream segment (e.g., procurement, wars, missions, etc., which involve heavy use of technology). As a result, our understanding of the bottom-up creation of technological opportunities (i.e., stimulating innovation through actual *use* of R&D *output*) is scarcer, relative to the top-down creation of technological opportunities by the government (i.e., stimulating innovation through *provision* of R&D *inputs*).[2] Motivated by this gap in the literature, we study how government-initiated downstream use of a new technology creates bottom-up spillovers, as measured by follow-on development of the technology and other related innovations.

In this work we also examine the extent to which local capabilities moderate the effect of new technological opportunities on innovation. In other words, to what extent do existing regional factors like knowledge base and human capital incentivize or assist local innovators to take advantage of new technological opportunities? There are two empirical challenges related to our research question that are particularly worth highlighting. First, the public sector simultaneously supports R&D investment and technology use in the private sector, making it difficult to disentangle the contribution of downstream technology use from upstream R&D investment. A second empirical challenge stems from difficulties in disentangling the geographical distribution of technology use from the geographical distribution of R&D because upstream research and downstream use tend to take place in the same location. For example, some of most cutting-edge academic research in agricultural biotechnology takes place in regional clusters where there has historically been a strong presence of agricultural industry (Sohn, 2017).

[2] This is not to say that the government's only role is to engage in "technological push" upstream without consideration for the downstream technical advances or commercialization. Indeed, the innovation literature has argued that upstream, basic research is essentially an outcome of practical, applied consideration (Rosenberg, 1982; Cohen et al., 2002).

In order to overcome these obstacles, we exploit a quasi-natural experiment in which a government initiative, the creation and expansion of the United States Post Office Department's (USPOD) Airmail Service in the early 20th century, created geographical and temporal variation in exposure to a new technology. Notably, the creation and expansion of the USPOD Airmail Service is quasi-exogenous to the local, geographical distribution of underlying R&D activities and other local capabilities (to be discussed in greater detail below). We develop and utilize a novel dataset on U.S. patents from the early 20th century and examine how the expansion of airmail impacted developments in aircraft technology within the regions where the airmail routes were opened. Accordingly, our work ties into recent scholarship examining the birth and the development of the aircraft and airline industry, including: Bryan's (2017) work showing how the European aircraft companies became technologically dominant by 1914 despite the airplane being a recent American invention; Hiatt, Carlos, and Sine's (2017) research depicting how nonmarket strategies, specifically stakeholder relationships to political and military actors, affected airline survival in Latin America between 1919 and 1984; and Goldfarb, Kirsch, and Moeen's (2017) historical account of technological progress during the establishment of a commercially viable airline industry.

We study how the entry of airmail into a county—a government-induced local shock to the use of technology in that county (with no direct shock upon local R&D inputs)—affected the amount and type of aircraft-related innovations, as measured by patents in that county. Aircrafts at this time were relatively crude devices, and so there was much room for improvement of the functionality and operation of aircraft. The opening of an airmail route into a county provided technological opportunities for inventors in those counties to interact with this new and evolving technology, which led to new innovations on aircraft features and designs. This exogenous shock provides a variation in technological opportunity across space and time, which allows us (1) to assess the causal link between the (government-induced) use of new technology in the private sector and the level and quality of local innovation, and (2) to assess the importance of local capabilities in exploiting the rise of new technological opportunities.

Our main finding indicates that aircraft-related patents increase by about 93% in counties that are served by airmail (what we define as "treated counties"). There does not appear to be any effect on patent quality, on average, but there is some indication that there are more high quality patents *and* more low quality patents. We also investigate the role of local knowledge base upon the local region's capability to exploit new technological opportunity, and find that differences in local knowledge bases may partially explain the bimodal effect on patent quality. Notably, different types of local knowledge base have a heterogeneous effect on patent quality. We find some evidence that treated areas with more local users and tinkerers produce more low-quality patents, whereas treated areas with aircraft specialists and higher education produce more high-quality patents, though the results are not definitive. This inquiry refines our understanding of how technological opportunities lead to advances in early-stage technologies.

Our paper makes several important contributions. First, our study builds on an existing literature on technological opportunities by studying the role of government in generating local innovation spillovers. Second, our findings contribute to the existing literature on the geography of innovation by demonstrating the importance of local use-driven opportunities in a nascent technology industry. By doing so, our research addresses the relative theoretical and empirical underdevelopment, as highlighted by Cohen (2010, sec. 4.2), towards extending our understanding of the role of institutionalized technological opportunity in facilitating innovation. Third, we draw from multiple historical texts to provide a detailed description of the early aircraft industry as it relates to airmail, and also of the state of aircraft technology in the first part of the 20th century. We use institutional details from this history to motivate our empirical analysis allowing us to contextualize innovation. Fourth, in order to conduct our empirical analysis we construct a novel dataset of U.S. patents from 1900-1940, and we will be making this dataset available for use by other researchers. We expect that providing access to this data will facilitate further scholarship related to historical instances of innovation and innovation processes. Finally, this study also offers some important practical implications with regard to building technological industries that involve uncertainties and risks during early inception. As such, our focused efforts in disentangling upstream spillovers stemming from the downstream use of early technologies provide important insights that can serve both scholars of innovation and policymakers.

RELEVANT LITERATURE AND THEORY

The Role of Government in Innovation: Top-Down Creation of Technological Opportunities

Despite questions as to its efficacy, it is generally accepted that the government plays an important role in overcoming market failure in private sector innovation (e.g., Nelson and

Langlois, 1983; Stiglitz and Wallsten, 1999; Martin and Scott, 2000). In particular, there exists a vast literature on how the government boosts private sector innovation through the provision of R&D inputs. On the one hand, the government creates technological opportunities by funding basic research and infrastructure, which creates positive spillovers for the target industry sector (e.g., Martin and Scott, 2000; Salter and Martin, 2001; Cohen, Nelson, and Walsh, 2002; Hall and Van Reenen, 2000; Arora and Cohen, 2015; Nagaraj, 2017). Notably, the growth and success of the U.S. pharmaceutical and biotechnology innovation is attributed to the public sector investments in biomedical research (Sampat and Litchtenberg, 2011; Li, Azoulay and Sampat, 2017). On the other hand, the government also supports innovation by allocating federal research budget to mission agencies like Defense Advanced Research Project Agency (DARPA), the Department of Defense (DOD), and the Department of Energy (DOE), which directly fund private R&D in the form of grants and subsidies (Joshi, Inouye, and Robinson, 2017; Howell, 2017).

In technological industries that serve heavy government procurement needs, like defense and aeronautics, the government actively engages in public-private R&D collaboration far beyond the scale of small and decentralized grants. For example, in order to resolve the crisis in rubber supply during the onset of World War Two, the U.S government closely collaborated with rubber companies and provided them with the resources and science to push for the fast development of synthetic rubber.[3] Technological developments derived from such modes of government-sponsored R&D also include the internet (Mowery and Simcoe, 2002), semiconductors, hardware, and software (Langlois and Mowery, 1996), and the major technological components of smartphones (Mazzucato, 2015).

Whereas such government initiatives are often implemented with an explicit goal to develop a certain technology, they also create unintended spillovers into related sectors. There are many examples of government initiatives that led to the creation of general-purpose technologies, which led to the rise of new technological industries. For example, the nuclear power reactor, now mostly used for civilian electricity generation, originated from the U.S. Navy's efforts to build nuclear submarines.[4] The development of the GPS for the military use eventually led to dozens of new technologies in the civilian industries, including transportation, logistics and communications.

[3] https://www.acs.org/content/acs/en/education/whatischemistry/landmarks/syntheticrubber.html
[4] https://www.theatlantic.com/technology/archive/2014/10/what-it-was-like-to-test-the-first-submarine-nuclear-reactor/381195/

The Role of Government in Innovation: Bottom-up Creation of Technological Opportunities

As discussed above, the supply side of government intervention, namely the top-down creation of technological opportunities from the upstream of R&D, has been widely examined in the innovation literature. However, the demand side of government intervention, namely the bottom-up creation of technological opportunities by government engagement in the downstream of R&D, is also an important topic of inquiry. On the one hand, the government can facilitate technological progress by itself being the first user of an innovation (e.g., Dalpé, DeBresson, and Xiaoping, 1992; Stiglitz and Wallsten, 1999; Edler and Georghiou, 2007; Aschhoff and Sofka, 2009), essentially creating early opportunities to gain technological feedback and learning. On the other hand, the government creates market demand and provides economic incentives in the civilian sector to adopt new innovation (Feder and Umali, 1993).

In this study, we shed light in particular upon the role of government in creation of technological opportunities by allowing for adoption of a new technology in the private sector, and thus encouraging technological feedback and learning. We believe this to be a relatively under examined yet important role of government in technological innovation. Technological progress is not isolated exclusively in activities of R&D researchers and engineers. Rather, how an innovation is practically used in a real-world setting also affects related innovations and technological advances. Rosenberg (1982) addresses this concept and proposes that subsequent innovations are enabled through a process of “learning by using” new technologies. Such a perspective moves the locus of innovation away from exclusively considering the manufacturer-as-innovator framework and establishes that the end-users of a technology are also a functional source of product and process innovation (e.g., Von Hippel, 1988; Tyre and Orlikowski, 1994; Chatterji and Fabrizio, 2012; 2014).

Feedback from use and trial is especially important in industries that involve high technological uncertainties and risks. Government involvement is often called for in such industries, because private companies often lack the incentives or resources to put their innovation to high-risk trials and errors. In the aircraft industry, our empirical setting, there exists substantial technological uncertainty in the design and production of a new aircraft and these uncertainties cannot be resolved until the actual flight (Mowery and Rosenberg, 1982). Unobserved or neglected technological issues have been exposed and resolved through continuous occurrences of accidents and failures, leading to new innovation such as air traffic control system, smoke sensors and fuel-inerting systems.[5] Remote-control and autonomous robotics technology experienced a rapid progress since the first deployment of iRobot's Packbots in rescue missions in New York following the events of September 11th, 2001 and the latter deployment of Packbots in Afghanistan. Although the DARPA-funded companies (such as iRobot) and university researchers had invested many resources in autonomous robotics technology, the actual deployment of the robots at the World Trade Center recovery site alerted them to technological features that needed to be developed, such as temperature sensors that protected the robots when penetrating burning rubble.[6]

Technological learning from such opportunities also often result in unintended spillovers into related sectors. Importantly, government use of military or aeronautical technologies often provide technological feedback that foreshadow the development of related industries in the civilian sector. For example, the deployment of military robots in warfare provided valuable learning opportunity, which eventually helped the launch of self-vacuuming robots in the household electronics industry. The early use of LIDAR technology in space missions also became the seed of innovation in other civilian technological industries, as seen in the invention of self-driving cars in the automotive industry.

The Role of Local Capabilities in Conversion of Technological Opportunities

Local capabilities become a focus of our investigation of technological opportunities and innovative output. In this way, we leverage the substantial amount of geographical variation for counties treated by airmail in order to explore how local conditions affect innovation. Vast literature has argued that technological spillovers arising from the upstream investment in basic knowledge and R&D are geographically bounded (Audretsch and Feldman, 1996). Similarly, technological opportunities arising from technological feedback and learning from downstream use is also geographically bounded because (1) technological feedback gained from use and feedback is often "sticky" and embedded within local inventors and companies that actually use the technology (Von Hippel, 1988), and (2) if such information gained by the actual users were to be transferred, it is likely to diffuse locally within the regional community of inventors.

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[5] http://www.popularmechanics.com/flight/g73/12-airplane-crashes-that-changed-aviation/

[6] http://www.nytimes.com/2001/09/27/technology/agile-in-a-crisis-robots-show-their-mettle.html

However, does a region having an access to the equal technological opportunity necessarily mean that the technological opportunity will convert into actual innovation output? For example, the advent of internet allowed ubiquitous access to new technological opportunities in information technology, certain regions have become the innovative leaders in IT, but not others. This motivates to ask us the question, assuming if new technology becomes accessible to use and experiment in certain locations, how would the pre-existing capabilities of each region shape local innovative activity?

The geography of innovation literature provides a long list of factors that spawn or support innovative activities within a locality: infrastructure, natural resources, institutions, universities, firms, skills, culture, and many more (Cooke, 2001; Maskell and Malmberg, 1999; Feldman and Kogler, 2010, Guzman and Stern, 2016). Such factors are called regional (local) innovation capacity or capabilities, with the literature emphasizing the role of local capabilities in the endogenous creation of technological opportunities within a region (Storper, 1997; Furman, Porter and Stern, 2002). Also important, but less highlighted is the role of regional capabilities to facilitate the conversion of often exogenous technological opportunities into innovation output (Nagaraj, 2017).

In particular, we are interested in the role of local knowledge base and whether a region has a supply of local innovators who have the knowledge and capability to understand and exploit technological opportunities. Relatedly, Cohen and Levinthal (1990) argued that the ability of innovator to acquire, interpret and apply new information (to the end output) is bounded by the existing prior knowledge, which is also called "absorptive capacity". Downstream use of technology will lead to more technological innovations to the extent that user-innovators have such capacity to diagnose, interpret and address any issues in the actual user experience. Such capacity is equally important for non-user innovators to vicariously learn from user input.

There exists substantial regional variation in the local knowledge base, since the supply of innovators in sectors that require tacit knowledge and skills is not as elastic as the supply of unskilled labor. This is because (1) cultivation of human capital is path-dependent, time-intensive, and costly; and (2) there exist significant adjustment costs when workers try to move into knowledge and research-intensive sectors from less knowledge-intensive sectors (Kerr, 2010). For example, the U.S. technological industry would not have been able to take full advantage of the economic potential of endogenous innovations without high-skilled immigration filling in the skill gap. Although such gap may be filled in the long term through movement of labor and investment in education and training, there should be a significant constraint on the supply-side of innovation due to short-term labor market frictions.

Having said that, we also note that there exists a demand-side constraint of regional innovation. Local market demand shapes the elasticity of regional innovation through the economic incentives of innovators to exploit and pursue technological opportunities. Although the direction of innovation is not entirely dictated by the pre-existing unmet needs and demand from the market, market demand for innovation does shape the allocation of R&D inputs and the intensity of innovative efforts (Mowery and Rosenberg, 1979). For example, university researchers become more productive in the scientific area of a technological opportunity if they find a greater chance of licensing out the output to a local incumbent firm (Sohn, 2017).

Within the remainder of this paper, we use the introduction of airmail in the United States to explore issues related to technological opportunity and innovation. We first examine the bottom-up spillover effect of technological opportunities arising from the government-initiated use of technology. Second, with regard to the role of local capabilities, we specifically focus on the role of local knowledge base from the supply-side of innovation, investigating how different abilities of local inventors shape the innovation output in response to the technological shock. Finally, we discuss how our findings contribute to the broader literature on innovation, considering impact on both theory and practice.

BACKGROUND AND EMPIRICAL SETTING

Aircraft and the Aviation Industry in the Early 20th Century

Aircraft technology, and the aviation industry in general, experienced rapid changes throughout the years between the First and Second World Wars (Launius and Bednarek, 2003). The United States Post Office Department's first airmail deliveries, commencing in 1918, were flown in World War One surplus Curtiss JN-4s. A single engine with only 90 horsepower powered these two-seat wood and fabric biplanes.[7] Notably, aircraft performance developed quickly, with dozens of firms producing hundreds of models and prototypes over the next two decades with no dominant design emerging until the late 1930s (Tushman and Murmann, 1998).

[7] https://airandspace.si.edu/collection-objects/curtiss-jn-4d-jenny

These rapid advancements are perhaps best exemplified by contrasting the Curtiss JN-4 with the Douglas DC-3, developed only twenty years later. The metal-constructed DC-3 was first flown in 1935 and had two engines producing 1,000 horsepower each; it reached speeds of over 200 miles per hour and would regularly cross the United States in just 16 hours; in addition to the increase in performance, the DC-3 carried up to 21 passengers in addition to mail and other cargo.[8] Appendix Figure 1 shows the drastic changes in airmail capabilities and costs between 1918 and 1939.

The Douglas DC-3 was also particularly significant in the history of aviation because it was the first aircraft to make commercial passenger traffic economically feasible. While airlines focusing on passenger travel started to emerge across the world in the late 1910s (see Hiatt, Carlos, and Sine (2017) for a look at commercial airlines in South America, from 1919 though 1984), prior to the introduction of the DC-3, passenger traffic was little more than an add-on for airlines (in Appendix Figure 1 we show the available data from Postmaster Annual Reports on the number of Airmail Passenger Miles in the mid-1930s). It is necessary, for our future analyses, that we note that the early airplane industry was built and developed around airmail.[9] Airmail contracts and subsidies ultimately influenced the expansion of the entire industry: "[E]arly seats, say on a trimotor of the late 1920s, were fairly rudimentary, with passenger service being something of an afterthought compared to mail and express."[10] For these reasons, it is important that we explore how government airmail activities affected aircraft-related innovations in the early 20th century.

Airmail in the United States, 1910-1940

During September 1910, 43,000 pieces of mail were carried on Long Island, NY as the first exhibition of airmail delivery in the United States. As such, the first mention of mail delivery by airplane appears under the heading "*Aeroplane Mail Service*" within the 1911 Report of the Postmaster General, which highlights the clear expectation that airplanes would soon play an important role in mail delivery:

[8] https://postalmuseum.si.edu/exhibits/current/airmail-in-america/the-airplanes/the-dc3s.html

[9] The broader development of the industry is clearly worthy of serious scholarly attention on its own, but it is largely beyond the scope of our paper. Our research, nonetheless, contributes to this understanding, and is focused on how early airmail contributed to the innovations that fostered the successful development of aircraft and commercial aviation.

[10] http://www.airspacemag.com/history-of-flight/aamps-interview-john-h-hill-97173767/?all

> *The progress being made in the science of aviation encourages the hope that ultimately the regular conveyance of mail by this means may be practicable. Such a service, if found feasible, might be established in many districts where the natural conditions preclude other means of rapid transportation.*

In line with this premonition, the USPOD extensively engaged with mail delivery by airplane over the next three decades. While the USPOD initially experimented with airmail in 1910, permanent delivery of mail by aircraft ultimately began on May 15th, 1918 when six converted United States Army Air Service (USAAS) Curtiss JN-4s began airmail delivery between Washington, DC and New York City.[11]

On August 12th, 1918, airmail delivery was transferred from the USAAS to the USPOD's new Aerial Mail Service, and this transfer resulted in a platform change to six purpose built JR-1B biplanes designed by Standard Aero Corporation. The JR-1B greatly expanded the capabilities of the USPOD Aerial Mail Service[12], which performed the first east-west service between New York and Chicago starting on December 17th, 1918. The USPOD Aerial Mail Service maintained operational control over airmail until The Kelly Act ordered the USPOD to contract airmail delivery to commercial carriers.

With the Wright Brother's first powered flight only occurring in 1903, the aircraft industry exhibited significant heterogeneity in technology and design. As such, it is unsurprising that early airmail was delivered with a variety of different aircraft platforms. No single design or firm dominated the airplane industry in the late 1910s and 1920s. Moreover, the changing airmail organization regularly introduced different aircraft platforms into service, with some of these airplanes being repurposed for mail delivery (often after seeing service in combat during World War One), and others being purposely designed and built for the specific job of mail delivery.

The move by the USPOD towards transferring airmail delivery to government contracts with private companies did not solidify the dominance of a single platform, but rather resulted in the emergence of dozens of aviation companies and furthered advanced the technological diversity of the airplane industry in the mid-1920s.[13] This diversity and technological development is exemplified by Charles Lindbergh's employment as an airmail pilot flying the de

[11] Annual Report of the Postmaster General: 1910-1919.
[12] http://about.usps.com/who-we-are/postal-history/standard-plane.pdf
[13] http://postalmuseum.si.edu/airmail/pilot/pilot_contract/pilot_contract.html

Havilland DH-4 biplane[14], Ben Eielson's development of an airmail route between Fairbanks and McGrath, Alaska in the Curtiss-Wright JN-D4,[15] and Elrey B. Jeppesen's development of flight maps designed specifically for pilots while he was flying the Boeing Model 40 Aircraft.[16]

Introduction and Expansion of the Airmail Routes

The first airmail route to open in the United States was between New York, NY and Washington, DC with a stop at Philadelphia, PA.[17] Although the experiment was successful and the Post Office Department started laying out plans for extending the routes, airmail was considered a novel yet unreliable means of postal transportation at the time. Few pilots were willing to risk flying at night, thus the early airmail routes were used only to complement and expedite mail delivery on the existing transcontinental rail line. Letters sent by airmail would travel by air during the day and then transferred to mail train at night. Before the full extension of the light beacon system on the transcontinental route by 1927, pilots were following the railroad tracks to make sure that they were staying on track.[18] Davies (1972) describes the development of the lighted airway system as "the greatest of all American contributions to the technique of air transport operation. [27]"

Airmail proved itself to be successful in the mid-1920s and regularly scheduled transcontinental service began on July 1, 1924. Congress passed the Kelly Act in 1925, which awarded government mail contracts to private carriers through competitive bidding. Postmaster General Harry S. New established feeder lines branched out from the transcontinental route to distribute regional mails. Appendix Figure 2 shows the spread of airmail routes, and depicts the transcontinental network of 18 routes that emerged by 1926.

Commercial Contract Air Mail (CAM) routes began operation on February 15th, 1926, Ford Air Transport, a subsidiary of Ford Motor Company, used a fleet of six custom Stout Metal Airplane's 2-AT Pullmans to fly mail on two routes: Detroit-Chicago and Detroit-Cleveland.[19] 34 permanent CAM routes were established over the next four years. At the industry level, when the Air Mail Act of 1930 was signed into law, longer-term contracts encouraged a series of mergers as larger diversified airplane companies sought these lucrative routes. By 1933, only

[14] http://postalmuseum.si.edu/airmail/pilot/pilot_contract/pilot_contract_lindy.html
[15] http://postalmuseum.si.edu/airmail/pilot/pilot_contract/pilot_contract_eielson.html
[16] http://postalmuseum.si.edu/airmail/pilot/pilot_contract/pilot_contract_jeppesen.html
[17] http://www.airmailpioneers.org/content/Sagahistory.htm
[18] http://paleofuture.gizmodo.com/the-highway-of-light-that-guided-early-planes-across-1466696698
[19] http://www.centennialofflight.net/essay/Government_Role/1925-29_airmail/POL5.htm

seven years after the introduction of CAM routes, the airmail network reached 39 distinct routes; Appendix Figure 3 highlights the extent of this expansion.

In 1934, congressional investigations of improper awarding of contracts temporarily reinstated the Army (now redesigned as the United States Army Air Corps (USAAC)) as the designated mail carrier. Because the USAAC was not properly organized or equipped to handle these operations, they suffered numerous accidents and fatalities in the winter and spring of 1934. This entire event, known as the Air Mail Scandal, concluded with the Air Mail Act of 1934, which reestablished commercial contracts for airmail delivery routes, broke apart vertically integrated holding companies, and separated manufacturing firms from transportation companies;[20] this market structure was largely maintained until the beginning of World War Two. By the end of 1940, airmail blanketed the country with nearly 60 million flight-miles of mail delivery occurring over 37,943 miles of established domestic airmail routes.[21]

Early Aircraft Technologies, Innovations, and Crashes

The expansion of airmail delivery over time and place (40 routes over 14 years) led to many opportunities for individuals to interact with the new technology. In particular, there were many forced landings that required fixing, and many aircraft design "bugs" that needed to be worked out. For example, in 1921 the post office recorded 1,764 forced landings, about half due to mechanical failures and half due to weather.

Airmail delivery was considered such an important, yet dangerous, activity that in 1931 congress authorized the USPOD to award (including posthumously) The Airmail Flyers' Medal of Honor to pilots working in the airmail service for "acts of heroism or extraordinary achievement."[22] A total of 10 medals were awarded, one posthumously, to airmail pilots, flying for 8 different companies for their heroism and achievements throughout the 1930s. Overall, dozens of pilots died in crashes caused by mechanical failures or inclement weather during the 1920s and 1930s, both while working directly for the USPOD or while flying as a CAM airmail pilots. Appendix Figure 4 depicts the number of airmail mechanical forced landings and crashes between 1919 and 1927.

[20] https://postalmuseum.si.edu/collections/object-spotlight/1934-airmail-scandal.html
[21] Annual Report of the Postmaster General: 1940-1941.
[22] H.R. 101. Public, No. 661. http://legisworks.org/congress/71/publaw-661.pdf

Airmail delivery provided an opportune environment for aviation-related innovations because aircraft and supporting technologies were still quite primitive. In fact, it wasn't until August 1920 that radio stations were installed at USPOD airfields, and 1921 until airmail was delivered across the country both day and night.[23] Clearly, there was ample room for radical and incremental improvements in aviation infrastructure, aircraft design, materials, engines, and complementary accessories.

Despite the clear limitations of aircraft and aviation infrastructure, airmail made great advances during the 1920s and 1930s. As quoted in Rosenberg and Macaulay (2006): "Machines break. Schedules suffer… [But] the mechanical problems would be sorted out eventually (p. 51)." This mindset contributed to the overall technological progress in aircraft. Rosenberg and Macaulay (2006) provide a number of other examples of the type of fixes and "debugging" that was needed for early airplane technology: "[T]he pilot immediately recognized that familiar clatter. It was the sound of a broken connecting rod. Time to go down (p. 169)." Some innovations were implemented by temporary fixes and later permanently incorporated through future designs: "[DeHavillands] were plagued by engine troubles, and their fuselages were unable to take the strain of landing in farmers' fields with their divots, holes, and furrows. Lightweight construction was causing them to flip over too easily, injuring pilots (p. 175)." Of course, some learning happened at extraordinary costs in terms of lives and equipment: "During a crash the fuel tank tended to rip loose, crushing the pilot (p. 176)."

This conclusion is not merely an ex-post framing of technological progress through the lens of users-as-innovators. Prominent authors from that era provide accounts that corroborate our perspective: "Prolonged experimentation with landing lights had led to the development of adequate wing tip lights, the light from which was not reflected into the eyes of the pilot by the propeller (David, 1934, p. 38-39)." In short, it is overwhelmingly evident that the expansion of U.S. Airmail into multiple geographies provided many opportunities for local inventors to improve upon existing airplane technology. In the remainder of this paper, we systematically analyze the effects of airmail expansion on innovation.

The Effect of Local Knowledge Base on Aircraft Innovations

[23] https://about.usps.com/who-we-are/postal-history/airmail.pdf

While the previous sections highlighted the overall development of airmail, our story (and our later empirical analyses) is necessarily a local story. When the USPOD established a particular route, the temporal local institutions and capabilities affected their ability to innovate on aircraft technology. As such, it is important that we highlight the different localized characteristics that facilitate technological advancements. In particular, we have argued that local knowledge base (i.e., the supply of innovators with relevant knowledge and skills) is important in the supply-side of innovation at the regional level. In particular, we focus on the respective impact of different types of local knowledge base: (1) the local supply of aircraft specialists and higher education and (2) the local supply of users and tinkerers.

A technological opportunity affords individuals and companies of the local area the incentive to innovate. We contend that the localized knowledge and capabilities of inventors in the region would result in a greater amount of novel innovations in response to the technological opportunity. Likewise, the type of existing knowledge may affect what types of innovations inventors make in response to such opportunity. For example, an exposure to the same technological opportunity may lead to very different types of innovations, depending upon the specific nature of skills and knowledge embedded in innovators. Fortunately, for the purposes of our investigation, the United States is a vast place with significant heterogeneity in knowledge across geographic space; since the selection of airmail routes was not driven by the pre-existing local knowledge base (as seen in Appendix Table 1), we therefore can exploit variation among the treated locations towards understanding how local knowledge base affects innovation.

The Local Supply of Aircraft Specialists and Higher Education. The first aspect of local knowledge base is the pre-existing supply of R&D knowledge and expertise. This is proxied by whether a treated region had had an early aircraft manufacturing company, as we consider that the most relevant source of technical knowledge for aircraft R&D at the time would be the early aircraft companies. The very inception of the U.S. aircraft industry during the late 1890s and the early 1900s was driven by a handful of aviation pioneers like the Wright brothers, Glenn Curtiss, Edson Gallaudet, and Grover Loening. These individuals acted quickly to incorporate companies and patent their inventions during the 1910s, seeing the vast potential of the technology. The early aircraft industry, following the First World War, was notably splintered, as many different firms and products competed for market share. The DC-3 Aircraft, which became the "dominant design" (Abernathy and Utterback, 1978) that reigned the industry in the late 1930s and 1940s, had not been introduced during our time period (1915-1935). This means that local aircraft companies had both the capabilities and the incentives to actively absorb technological feedback that arise from the regular flights of USPOD airmail planes to further develop and refine their nascent technologies.

Another important aspect of the local knowledge base is the strength of higher education. Although the early R&D of aircraft technology primarily involved trials and errors, scientific knowledge in aerodynamics became increasingly important with the advancement in engineering. In as early as the 1910s, universities such as MIT and University of Michigan started offering courses for aeronautical engineering and pilot training – which the most important figures in aviation history like Donald Douglas and Leroy Grumman had attended. Many of the nation's leading universities followed suit throughout the 1920s.[24] Knowledge spillovers and movement of personnel from academia played a key role in the development of the early aircraft companies, as shown in the case of Boeing and University of Washington,[25] and the case of Catholic University and the Curtiss Company.[26] We proxy the supply of higher education with the percentage of population in a given county between the age of 18 and 20 that are in education.[27]

The Local Supply of Users and Tinkerers. Although high-impact innovation in an established industry is often primarily driven by academic scientists and industry engineers, users and amateur inventors also play an important role during the early phase of technological development (Shah and Tripsas, 2007). While some early users and enthusiasts may remain as independent amateurs, others may move into industry as the founders or the employees of new companies, serving as key personnel of the nascent industry. In our setting, we proxy for the supply of such users and tinkerers in the region with the following two variables: (1) the existence of U.S Army airbase; and (2) the share of mechanical patents in the region's overall patent output.

[24] The year in which universities first started teaching adopted aeronautical engineering: MIT(1914), University of Michigan (1915), University of Washington (1917), University of Minnesota (1926), California Polytechnic State University of San Luispo (1927), University of Alabama (1928), Universiy of Cincinnati (1929), Iowa State University (1929)
[25] https://www.aa.washington.edu/AERL/KWT/history
[26] Dr. Zahm, Catholic University professor of mechanics, built one of the first wind tunnels, left academia to become the chief engineer of the Curtiss company; http://cuexhibits.wrlc.org/exhibits/show/vanished-buildings/buildings/wind-tunnel---catholic-univers
[27] At the time of our observation, there was an educational movement, led by Germany, for engineering-related higher education. This polytechnic model was in contrast to the liberal arts form of higher education that had long been the dominant form of post-secondary study in the United States. We have also compiled a list of the polytechnic colleges that were founded during or prior to the timeframe used in our study of aircraft. It is likely that aircraft were of particular interest to students and faculty of these polytechnic colleges because their purpose was to focus on pragmatic engineering matters. However, we could not use this variable in our analysis, because the number of treated regions with a polytechnic college is too few.

First, we proxy the local supply of potential user-innovators with the existence of the U.S. Army airbase in the region, as the military played an important role for the development of the nascent aircraft industry by training pilots, navigators and technicians. The existence of such trained users of the technology in a region means that the region would be better equipped to understand and exploit technical feedbacks that arise during actual operation of the technology. Following the end of World War One in 1918, the significant amount of military personnel deployed overseas began returning to the United States. One of the key war fighting developments to emerge from World War One was the role of military aviation for support and combat operations.[28] As such, the Army Air Service was inaugurated in 1918, and military installations across the United States started to train and organize aviation units. Individuals became familiar with airplanes through the military and often left to join early aircraft and airmail companies following their military service. One notable example is Charles Lindbergh who was trained as a pilot in the Army Air Service before embarking on his storied civilian aviation career, which included a stint as an airmail pilot. Leroy Grumman, the founder of what is now part of the aerospace giant Northrop Grumman, served in the U.S. Navy as a test pilot for flying boats.[29]

The local supply of tinkerers is proxied by the share of mechanical patents in the region's patent output. When a certain technological field is brand new and there is a general lack of scientific knowledge to guide technological search, inventors actively use their experience and heuristics from related fields (Feldman, 2000; Fleming, 2001). As such, we predict that the existence of experienced mechanics and engineers will increase the impact of a new technological opportunity, as the local inventors in other existing fields would likely also be the early pioneers and tinkerers of a fledgling industry. For example, some of the earliest innovations in aircraft technology are known to have been inspired by the mechanics of the bicycle or the automobile. Before the Wright brothers became fully engaged into aircraft invention, they were amateur inventors whose main job was repairing and manufacturing bicycles. They used the analogy of "a flying bicycle" to design their flyers and conduct experiments in aerodynamics.[30] As seen in the example of the Ford Trimotors or the Daimler fighters, the automobiles industry also acted as an important hotbed of future aircraft innovation.

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[28] The US Army Air Corps was formed in 1926 from the Army Air Service in order to provide a more operationally independent aviation command. https://www.army.mil/aviation/aircorps/
[29] http://www.northropgrumman.com/AboutUs/OurHeritage/OurFounders/LeroyGrumman/Pages/default.aspx
[30] https://www.bicycling.com/culture/thursday-december-17-1903

EMPIRICAL STRATEGY

We examine the impact of a region's downstream access to a new technology upon innovation output in the setting of the early U.S. Airmail industry between 1915 and 1935. The goal of our empirical analysis is to identify the impact of an airmail route opening upon the development of aircraft technology within the counties that are connected by the new routes. The key identification assumption of our analysis is that the assignment of airmail routes is quasi-exogenous to the level of aircraft technology due to the following set of reasons: (1) the selection of airmail routes is not driven by the level of aircraft technology in the region, (2) aircraft innovators or airline companies did not lobby for the opening of airmail routes in their counties, and (3) matching counties on a set of observables, like population and the stock of patents, balance out unobserved regional capacity that may be correlated with technological development (such as education, capital and engineering knowledge).

We undertake several steps to examine these identification assumptions, both qualitatively and quantitatively. Qualitatively, as outlined in the section above, historical anecdotes tell us that the first and second assumptions are likely to hold true. The airmail routes were first introduced as a way to complement pre-existing mail train deliveries. The very first routes were opened in the counties that were the key stops of the transcontinental railroad such as New York, Chicago, Salt Lake City, and San Francisco, and were operated by the government. Regional feeder routes were then chosen to branch out from these stops. The feeder routes were determined by the Postmaster General, who contracted them out to civilian carriers. The carriers acquired their planes from the retired airmail fleet, or ordered them from Curtiss, Douglas, or de Havilland, thus aircraft technology of a region was not necessarily a prerequisite for a route to open. Although the commercial airmail carriers did eventually move to passenger flight business, 80% to 95% of their early revenues came from airmail contract delivery[31] and the emergence of airline companies only came after the opening of airmail routes. Looking at the second concern, it is true that a few early aircraft manufacturers were born at the airmail hub locations, and some of them intentionally entered into airmail delivery, such as Ford and Boeing. However, being a transportation hub was not a prerequisite for the early rise of aircraft innovation. Appendix Figure 7 shows the geographical distribution of aircraft patents prior to 1918, along with some

[31] https://postalmuseum.si.edu/exhibits/current/airmail-in-america/contract-airmail-service/index.html

notable manufacturers. It shows that early aircraft innovation was geographically dispersed and very active in non-transportation hub locations such as Erie, NY and Dayton, OH.

To quantitatively address the first concern, we run a series of logit models to predict the timing of airmail entry into a county, and include the lagged level of aircraft patents in a county as one of several explanatory variables. The pre-existing stock of aircraft patents or the existence of early aircraft manufacturers do not seem to predict the timing of airmail entry; rather, county population seems to be the single most important variable (results are available in Appendix Table 1). This corroborates the historical evidence: the USPOD's goal is to deliver mail as quickly and efficiently as possible, and the best way to do this is to connect large population centers.

For the second concern, we match treated counties to a set of control counties on the covariates that are correlated with aircraft technology: the level of population, the sum of patents filed prior to 1918, the presence of early aircraft manufacturers, and the presence of Army aviation bases. These covariates are chosen because they are correlated with both the designation of a county as a stop in an airmail route and the level of aircraft patenting in the county. Population and patents of a county control for the designation of an airmail route due to their larger mail volume and economic importance. The presence of aircraft manufacturers and Army aviation bases control for the designation of an airmail route due to strategic importance of the location in terms of air transportation, as well as other unobserved characteristics potentially in favor of aviation.

The matched controls are selected by propensity score matching method (Rosenbaum and Rubin, 1983; Dehejia and Wahba, 2002). We use the PSMATCH2 propensity score matching module in Stata to match samples (using the nearest four neighbors[32]). Four variables have been used: (1) a county's logged population of year 1920 (taken from the 1920 Decennial Census), (2) a county's sum of patents filed between 1900 and 1917 (the year before the first treatment), (3) the presence of an aircraft manufacturer in a county prior to the treatment, and (4) the presence of an Army aviation base in a county. Appendix Table 2 and 3 lists the counties in the treatment and control samples, grouped into four buckets based on the population in 1920 and pre-1918 stock of aircraft patents.

[32] The results are robust to using different numbers of nearest neighbors (e.g., three or five). Available upon request.

All estimations were conducted using conditional fixed effects Poisson regression since the outcome is a count variable. Conditional fixed effects Poisson models correct for overdispersion and allow for cluster-robust standard errors (Wooldridge, 1997).[33] All regressions include the weights generated from propensity score matching.

DATA

For this project, we matched historical data on airmail routes to a novel dataset on U.S. patents. We obtain the information on airmail routes from David (1934) and from annual reports to Congress by the U.S. Postmaster General. To construct the patent dataset, we downloaded patent PDFs from the U.S. Patent & Trademark Office (USPTO) for all patents granted between 1900 and 1940.[34] We then scraped the patent text for relevant information including inventor name, location, and assignee name. We also supplemented this information with data scraped from Google patent database (i.e., filing date, grant date, international patent class, U.S. patent class, forward citations).

Inventor information was then fuzzy-matched (because of many typos) to a U.S. address dataset. We assign patents to the category "aircraft" if the word "aircraft" (including related words and variations such as airplane, etc.) appears in the title or main text, or if it is classified as aircraft related (IPC B64 and B21D 53/92; USC 244). We conduct some robustness tests that focus only on the patents classified as USC 244, but based on our analysis of a random sample of individual patents, relying solely on USC 244 misses a substantial number of aircraft-related patents. Appendix Figure 5 presents the total number of patents by year also separated into patents falling into USC 244 and those within other patent classes but designated as aircraft-related. We also create patent counts for "related non-aircraft" patents, which are patents that are not "aircraft" but that have a primary USC code that was ever listed as a secondary USC code on one of our "aircraft" related patents. Examples of these types of patents include automobiles (land vehicles), internal combustion engines, geometrical instruments, radio wave systems, etc. We also create patent counts for "unrelated non-aircraft" patents, which are patents that are not "aircraft" and that do not have a primary USC code that was ever listed as a secondary USC code on one of our "aircraft" related patents. Examples of these types of patents include mining, steam

[33] The results are robust to using the conditional fixed effects negative binomial estimation (included in the Appendix).
[34] While this includes more years than used in the current analysis, we anticipate using the data on other projects, and providing the data for other researchers to use.

engine, railroads, milling, spring (or animal) powered motors, etc.

For the analyses described below, we use various patent based measures that have been aggregated to the county-year level based on year of filing. However, as a check on our method, we compare our state-year patent grant counts to state-year patent grant counts from USPTO,[35] having obtained the state-year patent grant counts from the USPTO's *Technology Assessment & Forecast, Seventh Report*, dated March 1977.[36] The raw correlation between our state-year counts and those of the USPTO is 0.964. As an additional check, we visually inspect the correlation for each state. This check, presented in Appendix Figure 6 for six of the large patenting states, reveals that our counts are, on average, below the counts that appear in the USPTO but appear to be consistent (i.e., the changes from year to year are about the same), indicating that our data accurately captures patenting activity.[37]

Dependent Variables

Our primary dependent variable is a count of patent applications (that were ultimately granted) at the county-year level. We construct these counts for aircraft patents (which is our main dependent variable), as well as aircraft-related patents and patents unrelated to aircraft (See Data Section for details on the construction of these variables). We also construct various measures of aircraft patent quality that we use as dependent variables, including the average number of forward citations per patent in the county-year, the standard deviation of forward citations to patents applied for in the county-year, and counts of the number of patents with forward citations falling in the bottom 10%, bottom 25%, top 25%, and top 10% of the distribution of forward citations to aircraft related patents in that year.[38]

Independent Variables and Controls

Our main independent variable is an indicator for an airmail route being opened into the county at the county-year level called *post-entry*.[39] We also create indicators for whether there are single

[35] Note that the data we have assembled allows us to aggregate to any geography-year for year of application or any geography-year for year of grant. For our analyses, we aggregate to the county-year for year of application. USPTO only provides counts at the state-year for year of grant, which is not suitable for our analysis, but is suitable as a way for us to check our data against the USPTO data.
[36] We thank Jim Hirabayashi at the USPTO for providing us with a copy of the report.
[37] Additional details on the various tests are available from the authors.
[38] Note that the forward citations on the aircraft patents come from patents granted after 1947, as the practice of citing prior art in patents only started in 1947. Thus, it is fair to say that we are using forward citations as a proxy of exceptional quality and foundational technology (considering that these patents are cited by inventors of several decades later), rather than a measure of knowledge spillovers.
[39] There are two cases in which the actual location of the airport is outside of the county boundary of the focal city (Washington DC's Airport is located in Arlington County, VA; New York City's main airport became the Newark Airport in Essex County, New Jersey). Our result assumes

or multiple routes into the county. Only the origin and the destination counties were coded as treated, not intermediate stops. As pilots and planes only made a short stop at the intermediate stops for mail drop-off and refueling, flight debriefing and the subsequent efforts to address the technical issues are likely to have taken place at the terminus locations.[40] Before matching, we dropped from the treated group several outlier counties at the right tail of the economy (San Francisco, CA; Cook, IL; Suffolk, MA; New York, NY; Allegheny, PA; Philadelphia, PA). The population and the patenting of such counties were considered too big to find the right controls, and the inclusion of such counties weakened the covariate balance.[41]

As to alleviate concerns that the opening of airmail routes may be endogenous to pre-existing innovation capacity of the counties, we use a propensity-score matching technique (described above) to identify 83 untreated counties that are similar[42] to 34 treated counties based on the population and the manufacturing capacity of year 1920 Census, as well as the sum of aircraft patents and the sum of non-aircraft patents between 1910 and 1917, and the existence of early aircraft manufacturer and Army airbase.[43]

Anecdotally, routes were chosen to join the largest population centers together in the most efficient way possible, and to connect cities on the West Coast to the East Coast as quickly as possible (with a specified focus on New York City and San Francisco). The earlier routes were established along the East-West Transcontinental Railroad, followed by regional feeder routes. County population is the single most important variable in hazard models predicting the timing of an airmail route opening in a county.[44] We therefore include time-varying *population* in most of our regression models.[45]

For our analyses on local knowledge base, we focus on four variables: incumbent manufacturer, percentage of higher education, the presence of an Army airbase, and the share of mechanical patents. The first two focus on the supply of aircraft specialists and highly educated

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that all the counties within the city boundary as treated (e.g. New York County), even if the airport is not located in those counties. Results are largely consistent even if those counties are considered as untreated (results available upon request).

[40] Davies (1972) reports that many of these stops were eliminated as airplanes with longer range capability were adopted. We replicated our analysis using the intermediate stops as treated and did not find a result (results available upon request). Although repairs were often performed at these emergency landing fields, it seems that such activities did not lead to patenting.

[41] These counties had the stock of pre-1918 non-aircraft patents greater than 20,000, or the bank deposit of year 1920 greater than $700,000. This cut-off values were chosen in order to maximize the covariate balance. The main results are consistent if we use different cut-offs (although the covariance balance may be weaker). These results are shown in Appendix Table 6 and Table 7.

[42] We use historical census data from Haines (2010) and interpolations from Fishback et al. (2011) to develop an appropriate matched sample.

[43] Additional details on the matching are available from the authors.

[44] Additional details on the hazard model are available from the authors.

[45] Population is also the only demographic variable that is available in all years at the county-year level. Other demographic variables are available for the decennial census years only. In unreported analyses available from the authors we conduct robustness tests limited to the decennial census years that include additional demographic control variables. Results are similar.

workers, whereas the second two focus on the supply of users and tinkerers. *Incumbent manufacturer* is a dummy variable for all counties in which an incumbent aircraft manufacturer was based prior to 1918 (the start of airmail). The incumbent manufacturer dummy may be indicative of strong knowledge and incentives to invent and commercialize aircraft technologies. *Percent of higher education* is created by counting the total number of individuals in a county in schooling between the age of 18 and 20, as indicated in the 1920 Census (this data is available every 10 years from the U.S. Census Bureau), and dividing this number by population in the county in 1920.

The presence of an *Army airbase* is a dummy variable that equals one if the county had a U.S. Army base with aircraft landing facilities prior to 1918 (the U.S. Air Force was created after World War Two and military aviation, prior to the establishment of the Air Force, fell under the command of the U.S. Army and Navy).[46] U.S. Army pilots and the mechanics that worked on their planes were a source of labor for the USPOD airmail, and a potential source of ideas for how to innovate based upon new feedbacks from the repeated flights.

The *mechanical patent share* is created by counting up the number of patents in a county-year that are classified as "mechanical" and dividing by the total number of patents in the county-year. This number is averaged across the years 1910-1917 (i.e., the eight years prior to the creation of private airmail) for each county. Counties with a higher proportion of mechanical innovations will be better positioned to apply their experience for aircraft technology development.

Table 1A presents the summary statistics of the outcome variables for the treated counties and the control counties. Table 1B uses a number of select demographic variables from the 1920 Census together with patent data to show that the treated and the control counties are well-balanced on pre-treatment covariates that may be relevant to innovative capacity of the county. As noted above, only four county level variables were used for the propensity score matching—population for year 1920 (taken from the 1920 Decennial Census), sum of patents filed between 1900 and 1917, the presence of an aircraft manufacturer, and the presence of an Army airbase—but matching helped achieve a balance also for other potentially relevant economic variables, providing a lot of confidence in our matching approach. Although the mean of certain covariates,

[46] The data on Army bases with aircraft landing facilities was collected from various government and archival sources including from the US Army (http://www.history.army.mil/html/forcestruc/orghist.html), Air Force (http://www.afhra.af.mil), and Army Aviation Museum (http://www.armyaviationmuseum.org).

such as population and manufacturing establishments, seem to be slightly greater for the treated than the control, propensity score matching effectively reduces the differences to small and statistically insignificant (See Table 1C).

RESULTS

The Impact of Airmail Route Entry on Number and Quality of Patents

For most of our results we use data on patent applications between 1915 and 1935, unless otherwise specified. We choose this date range because 1915 pre-dates the creation of the first U.S. airmail route in 1918, and 1935 is the year that the USPOD is reorganized by Congress. Our first set of results, presented in Table 2, is a set of Poisson models investigating the effect of an airmail route opening in a county-year on the count of aircraft patents in that county-year. All the results include county and year fixed effects, and standard errors are clustered at the county level. Model 1 presents results for all years and all counties (treated and control) without population control. Model 2, our baseline result that we replicate in other tables described below, replicates Model 1 and includes population control. In this model, the coefficient on *post-entry* is positive and significant, indicating that the opening of an airmail route leads to an increase in aircraft patents. Using the coefficient on *post-entry* from Model 2, we interpret the results to mean that, following entry of an airmail route into the county, there is an approximately 93% ($e^{0.658}$-1=0.93) increase in the number of aircraft patents, on average. Model 3 replicates Model 2 but restricts the years to 1915-1930 in order to avoid potential confounding effects from the Great Depression and the Airmail Act of 1930 (which consolidate the ownership of the airmail routes). Model 4 replicates Model 2 but restricts the counties to treated counties only. The results are consistent across all of these models; the entry of an airmail route appears to lead to higher quantity of patenting.

The final model in Table 2 investigates whether the changes we document in Models 1 – 4 are at the intensive or extensive margin. To this end, Model 5 provides a logit model in which a county is coded as one in the year when it applies for an aircraft-related patent for the first time during the observation period, or zero otherwise (observations after the county's first aircraft patent are dropped). The coefficient on post-entry is not significant, suggesting that there is little change in the extensive margin. Instead, most of the increase in patenting activity is from counties that already had been patenting in aircraft related technology, and are now patenting more than before.

Figure 1 plots the coefficient estimates from the regressions in which the number of aircraft patents is regressed upon the interaction terms between the treatment dummy variable (the entry of an airmail route to a county) and a suite of indicator variables that each correspond to the number of years before/after the treatment event. We investigate the effects for 5 years before/after treatment (the years prior to year -5 were clustered together with year -5, same with +5 years). Robust standard errors were clustered around at the county level. The dashed gray lines show the 95% confidence intervals around these estimates. The graph does not reveal any evidence of a pre-treatment effect (i.e., the confidence intervals for the pre-treatment coefficients overlap with zero and show no obvious trend). The graph suggests an uptick in patenting following entry, with the clearest evidence coming from years 3 and 4 after entry.

Table 3 compares our main results with the effect of airmail entry on related and unrelated patents (note that Model 1 of Table 3 replicates Model 2 of Table 2 as to serve as a comparison for the other Models included in Table 3). Model 2 of Table 3 breaks out *post-entry* into counties with multiple routes and counties with a single route. We expect that treatment will be stronger in counties with more routes (as there are more planes and hence more opportunities for inventors to tinker with the technology). Indeed, the coefficient on *post-entry*multiple routes* is positive and significant, whereas the coefficient on *post-entry*single route* is not significant. Models 3 through 6 investigate the effect of airmail entry on non-aircraft patents. Models 3 and 4 use patents in areas related to aircraft (but not aircraft patents themselves) as the dependent variable. This allows us to investigate if there are additional unintended spillovers from the introduction of airmail on inventions in adjacent technological spaces. We find only limited evidence that the introduction of airmail led to innovations in related areas. In Models 5 and 6, we use the count of unrelated non-aircraft patents as our dependent variable. These last two models can therefore be thought of as a placebo test. We find that the *post-entry* coefficients are not significant for these two models, lending credibility to our main results inasmuch as the effects of aircraft technological opportunity should be relatively isolated (i.e., airmail leads to aircraft innovations as opposed to other innovations because the increase in patenting is specific to the technological opportunity).

However, it is also worth noting that the *post-entry* coefficients are positive (though insignificant) across both related and unrelated innovations, which is consistent with previous literature that has shown a positive effect of transportation on innovative activity (e.g., Agrawal, Galasso, and Oettl, 2017; Perlman, 2015). The reason that we do not find a significant impact of airmail on other innovation output is probably because the effect of transportation on innovation is realized through the movement and encounters of people, yet passenger travel was only in its infancy during our observation period.

Our next set of results, presented in Table 4, investigates the effect of airmail route entry on patent quality. To do this, we run models similar to Model 2 in Table 3, but on various forward citation based measures of patent quality. Model 1 replicates Model 2 from Table 3 on the average number of patents. The dependent variable in Model 2 is the average number of forward citations to patents applied for in a given county-year. The coefficient on *post-entry* is positive but not significant. The dependent variable in Model 3 is the standard deviation of the number of forward citations to patents applied for in a given county-year. The coefficient on *post-entry* is positive but not significant. Models 4 through 7 explore the tails of the quality distribution to understand whether any increase in variance (Model 3) is a result of an increase in one or both of the tails of the distribution. The coefficients on *post-entry* for the count of patents falling in the bottom 25^{th} percentile is positive and significant at the 1% level, whereas the count of those in the top 25^{th} percentile is positive but insignificant. Interestingly, there is a large increase in patents in the top 10^{th} percentile for the treated counties. This suggests that although the entry of airmail routes did have a positive impact upon the highest end of the quality distribution, the overall quantitative impact was driven by the increase of the lower-quality patents. However, since airmail routes led to more patents at the both ends of the quality distribution, there was an ambiguous effect on patent quality, on average.

The Role of Local Knowledge Base

Tables 5 through 8 investigate the role of the different types of local knowledge base. Each of the tables presents results on counts of patents (Model 1), forward citations (Model 2), standard deviation of forward citations (Model 3), and quality distribution (Models 4 through 7). Tables 5 and 6 focus on the local supply of specialists and higher education, respectively. Tables 7 and 8 focus on the local supply of users and tinkerers.

Table 5 focuses on the presence of an incumbent aircraft manufacturer. We interact the incumbent manufacturer indicators with *post-entry* (the main effect on these indicators is absorbed by the county fixed effect). The results in Model 1 suggest that entry of airmail into the county leads to a higher number of patents for both types of counties. The coefficient on *post-entry*incumbent* is positive and statistically significant. Similarly, the coefficient on *post-entry*no incumbent* is positive though not as statistically significant. While the coefficient values appear different, we cannot reject that they are the same, statistically. The coefficient on count of patents with forward citations falling in the top 25% is positive and significant at the 5% level, for counties with an incumbent manufacturer, providing some evidence that the increase in patents in counties with an incumbent manufacturer are of higher quality. However, interestingly, counties without an incumbent manufacturer also produced patents at the highest end (i.e., the top 10^{th} percentile in terms of forward citations) of the quality distribution.

Table 6 focuses on the share of educated population in the age between 18 and 20, which is the proxy of the region's supply in higher education. We indicate the counties as having "high" or "low" education based on whether the share of educated workforce is above or below the median value, respectively. We then interact these indicators with *post-entry* (the main effect on these indicators is absorbed by the county fixed effect). The results in Model 1 suggest that entry of airmail into the county leads to a higher number of patents for both types of counties. The coefficient on *post-entry*education high* is positive and statistically significant. Similarly, the coefficient on *post-entry*education low* is also positive and statistically significant, but of smaller magnitude. As in the previous cases, we cannot reject that the coefficient values are the same, statistically. The coefficients on count of patents with forward citations falling in the top 25% and top 10% are both positive and significant at the 5% levels, for high education counties. This provides some evidence that the increase in patents in counties with a high level of education are of particularly high quality, and that higher education, which is the source of scientific knowledge, is an important foundation of high-impact innovation.

Table 7 focuses on the presence of U.S. Army airbases. We interact the indicators "airbase" or "no airbase" with *post-entry* (the main effect on these indicators is absorbed by the county fixed effect). The results in Model 1 suggest that entry of airmail into the county leads to a higher number of patents for both types of counties. Both of the coefficients on *post-entry*airbase* and *post-entry*no-airbase* are positive and statistically significant. Models 4 through 7 suggest that the *airbase* counties experienced an increase of patents in the left tail of quality distribution, whereas the *no-airbase* counties experienced the increase mostly in the right tail. Overall, we find that the treated counties with the army airbases mostly came up with a greater number of low-quality patents, whereas the treated counties without the army bases experienced a relatively smaller increase in number of patents, yet these patents were of high quality. Note, however, that while the coefficient values appear different, we cannot reject that they are the same, statistically.

Table 8 focuses on the share of mechanical patents, which proxies for the local supply of tinkerers. We indicate the counties as having “high” or “low” share of mechanical patents based on whether the share is above or below the median value, respectively, of the share of patents applied for in 1912-1917 (the prior 5 years before airmail started) that were classified as mechanical. We then interact these indicators with *post-entry* (the main effects on these indicators is absorbed by the county fixed effect). The results in Model 1 suggest that entry of airmail into the county leads to a higher number of patents for both types of counties. Both of the coefficients on *post-entry*high share* and *post-entry*low share* are positive and statistically significant. The increase in the number of patents for the high share treated counties is primarily driven by patents of lower quality. On the other hand, the low share treated counties experienced an increase in both ends of the quality distribution. Overall, the results suggest that the share of mechanical patents is not a prerequisite for inventors to take advantage of the new opportunity. Rather unexpectedly, counties that have not had a strong local presence of mechanical technology are exploiting the new opportunity more actively. This could imply that the pre-existing strengths in other technological areas may prevent inventors from moving into a newly growing area. However, although the coefficients of the high share and low share counties appear different, we cannot rule out that the coefficients are the same across high and low share counties due to the lack of statistical power.

To recap, Tables 5 through 8 investigate how different types of local knowledge base shapes the impact of airmail entry upon the quantity and quality of aircraft innovation. While local capacities do appear to enhance the effects a bit, there is little evidence to support the idea that having a high degree of local capabilities is a necessary ingredient to enjoy the benefits of a technology opportunity. More specifically, there is limited evidence that having an incumbent manufacturer, a higher amount of educated workers, or an army airbase enhances the effect of airmail entry. It does appear, however, that having a lower share of mechanical patents enhances the effect of airmail entry. There is also some evidence that local capabilities have heterogeneous effects on patent quality. While the presence of an incumbent manufacturer (i.e., the presence of specialists) or a higher amount of educated workers does not appear to affect differences in patent quality much, the presence of an airbase (i.e., more users) and a higher share of mechanical patents (i.e., more tinkerers) is associated with more lower quality patents, following airmail entry.

Overall, however, it is difficult to detect systematic statistically significant differences between the coefficients on high local capability and those of low capability, as shown in the F-statistics and the confidence interval overlaps. These results could mean that these local capabilities are sufficient but not necessary conditions of innovation, or it could simply be due to the limited number of our data points and the subsequent lack of statistical power. With the second possibility, we cannot reach a definitive conclusion to our research question about the role of local capabilities in innovation. The general conclusion from the results implies that different types of capabilities play a different role in the downstream application of a nascent technology.

DISSCUSSION AND CONCLUSION

We use the establishment of airmail routes to offer insights into how technological opportunities and local capabilities affect aircraft-related innovation between 1915 and 1935. By extending access to aircraft (a nascent technological opportunity) and providing incentives for technological improvements, these airmail routes shift the locus of innovation to the private sector and increases aircraft-related patenting. In addition to developing and refining our understanding of innovation processes, our research also contributes to the wider entrepreneurial, innovation, and institutional literatures by demonstrating how government procurement can act as a source of technological opportunity.

By exploiting a natural experiment, the establishment of airmail routes, we are able to study how access to technology affects innovation. We are also able to assess the relative importance of local capabilities. From our analysis of aircraft patents during the early 20th century, we are able to provide two major research contributions in this work: (1) we document how a government initiative in the downstream use of a nascent technology can spur innovation in the private sector, and (2) we demonstrate that local capabilities have some effect on the innovation—including the quality of the innovation—but are not a limiting condition.

While our results ultimately sum to a single case study, we provide a comprehensive investigation of how technological opportunities, together with local capabilities, can affect the quantity and quality of innovation. These results, of course, do not suggest that all such efforts by policy makers to increase access to new technologies will similarly affect innovation, nor that the government always does a good job selecting and pushing the downstream use of a new technology. However, we believe that our work establishes a framework for future research to investigate under what conditions government adoption and use of new technologies support innovation. Such an agenda would broadly contribute to an improved understanding of the role of the institutionalized environment in technological advances.

Our findings complement other studies showing how government investment in transportation networks can increase innovative activity more generally, either via increased knowledge flows or easier access to potential markets (Sokoloff, 1988; Agrawal et al., 2016; Perlman, 2015). Pragmatically, we show that something as simple as opening up an airfield can have important consequences for future innovation. While still more research is needed in order to develop richer models of innovation and technological development, the findings presented in this paper, nonetheless, advance existing theory and contribute to our understanding of innovation processes. Likewise, this research highlights the unexpected bottom-up (i.e., from the downstream to the upstream of the value chain) spillovers of government procurement decisions and offers important insights for public policy.

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Table 1A: Summary Statistics

Variable	Obs	Mean Treated	SD Treated	Min Treated	Max Treated	Obs	Mean Control	SD Control	Min Control	Max Control
Year	714	1925	6.06	1915	1935.00	1743	1925.00	6.06	1915	1935.00
Aircraft Patents	714	1.5	3.47	0	31.00	1743	1.50	4.21	0	41.00
Non-Aircraft Patents	714	104.03	185.58	0	1135.00	1743	84.52	86.54	0	410.00
Avg. Forward Citations	714	1.39	4.28	0	64.00	1743	1.62	4.47	0	73.00
SD of Forward Citations	714	0.33	0.94	0	8.00	1743	0.40	1.50	0	15.00
Patents of Bottom 10% Cites	714	0.47	1.31	0	14.00	1743	0.52	1.66	0	15.00
Patents of Bottom 25% Cites	714	0.15	0.53	0	5.00	1743	0.13	0.52	0	5.00
Patents of Top 25% Cites	714	0.3	0.90	0	7.00	1743	0.35	1.13	0	12.00
Patents of Top 10% Cites	714	0.75	2.15	0	21.97	1743	0.93	3.54	0	53.74

Table 1B: Treatment and Control Samples

Variable	Mean Treated	SD Treated	Mean Control	SD Control	T-stat (p-value)
Controls Used in the Propensity Score Matching					
Total Population (1920)	342638.91	7.13E+04	263209.22	35806.18	1.00 (0.322)
Manufacturing Establishments (1920)	1019.53	236.83	818.95	128.31	0.74 (0.458)
Existence of Early Aircraft Manufacturers	0.32	0.08	0.3	0.05	0.23(0.819)
Existence of Army Airbases	0.32	0.08	0.31	0.05	0.15(0.879)
Pre-1918 Sum of Aircraft Patents	6.97	1.69	7.54	1.52	-0.25 (0.804)
Pre-1918 Sum of Non-Aircraft Patents	922.41	242.07	987.46	111.45	-0.24 (0.808)
Controls Not Used in the Propensity Score Matching					
Urban Population (1920)	311486.06	7.07E+04	221516.47	34954.97	1.14 (0.256)
Population Density (1920)	2103.08	964.49	811.1	238.59	1.30 (0.196)
Population in Schooling, 18-20 (1920)	2120.35	383.23	1758.66	225.75	0.81 (0.418)
Male Population, 18-44 (1920)	82451.32	17446.43	58614.59	8261.6	1.23 (0.219)
No. of Manufaturing Wage Earners (1920)	38171.65	9825.9	38467.17	5783.1	-0.03 (0.979)
Value of Manufacturing Output, 18-44 (1920)	2.93E+08	7.30E+07	2.66E+08	4.50E+07	0.31 (0.759)
Manufacutring Value Added, 18-44 (1920)	1.16E+08	3.30E+07	1.04E+08	1.70E+07	0.32 (0.751)
Bank Deposit (1920)	113034.7	25353.31	77147.06	8692.23	1.34 (0.183)

Table 1C. Covariate Balance in the Full Sample

Variable	Treated	Control	Differences	T-Stat (P-Value)
Total Population (1920)	416792.66(93110.46)	31417.84(1608.29)	3.9e+05(93124.35)	4.14(0.000)
Urban Population (1920)	380335.78(90942.73)	13889.96(1539.06)	3.7e+05(90955.76)	4.03(0.000)
Population Density (1920)	1966.76(642.02)	84.54(14.11)	1882.23(642.1)	2.93(0.003)
Population in Schooling, 18-20 (1920)	2600.32(485.94)	249.70(8.80)	2350.62(486.0)	4.84(0.000)
Male Population, 18-44 (1920)	100606.65(22581.52)	6480.07(375.56)	94126.58(22584.65)	4.17(0.000)
Manufacturing Establishments (1920)	1431.30(367.38)	78.50(5.59)	1352.80(367.4)	3.68(0.000)
No. of Manufaturing Wage Earners (1920)	55294.15(14614.77)	2462.37(231.13)	52831.78(14616.59)	3.61(0.000)
Value of Manufacturing Output, 18-44 (1920)	4.37e+08(1.2e+08)	1.60e+07(1.8e+06)	4.2e+08(1.2e)	3.53(0.000)
Manufacutring Value Added, 18-44 (1920)	1.70e+08(4.7e+07)	6376299.50(6.8e+05)	1.6e+08(4.7e)	3.49(0.000)
Bank Deposit (1920)	245521.67(62607.38)	6733.58(315.21)	2.4e+05(62608.18)	3.81(0.000)
Pre-1918 Sum of Aircraft Patents	9.76(2.67)	0.34(0.03)	9.42(2.67)	3.53(0.000)
Pre-1918 Sum of Non-Aircraft Patents	1773.12(555.69)	50.68(3.55)	1722.44(555.7)	3.10(0.002)

Table 2: Main Results

	(1)	(2)	(3)	(4)	(5)
	Aircraft Patents 1915-1935	Aircraft Patents 1915-1935	Aircraft Patents 1915-1930	Aircraft Patents Treated Counties Only 1915-1935	Aircraft Patenting Begins in County 1915-1935
Post-Entry	0.773***	0.658***	0.740***	0.459*	-1.210
	(0.174)	(0.194)	(0.185)	(0.256)	(1.046)
Population		0.882	1.694***	0.512	0.836***
(logged)		(0.387)	(0.466)	(0.422)	(0.234)
County FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
Obs	1890	1890	1424	630	827
Group	90	90	89	30	117
Log Likelihood	-1548.87	-1540.10	-1149.37	-653.09	-127.19

Standard errors in parentheses, clustered by county; * p < 0.10, ** p < 0.05, *** p < 0.01

All regressions weighted by propensity score matching weights

Models (1)-(4) report conditional fixed effects Poisson regression estimates; Model (5) reports Logit regression estimates

Table 3: Heterogeneous Treatment

	(1) Aircraft Patents 1915-1935	(2) Aircraft Patents 1915-1935	(3) Related Patents 1915-1935	(4) Related Patents 1915-1935	(5) Unrelated Patents 1915-1935	(6) Unrelated Patents 1915-1935
Post-Entry	0.658*** (0.194)		0.139 (0.094)		0.035 (0.071)	
Post-Entry * Multiple Routes		0.721*** (0.203)		0.132 (0.091)		0.019 (0.065)
Post-Entry * Single Route		0.253 (0.231)		0.181 (0.189)		0.127 (0.165)
Population (logged)	0.882** (0.387)	0.867** (0.398)	0.850*** (0.154)	0.858*** (0.156)	0.758*** (0.152)	0.773*** (0.150)
County FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Obs	1890	1890	2331	2331	2436	2436
Group	90	90	111	111	116	116
Log Likelihood	-1540.1	-1537.78	-2707.52	-2707.33	-6083.19	-6073.83

Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All regressions weighted by propensity score matching weights

Table 4. Distribution of Quality

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Count of Patents With Forward Citations that Fall Into The:			
Dependent Variable	Average Patents	Avg. Citations Per Patent	Standard Dev. of Citations	Bottom 10%	Bottom 25%	Top 25%	Top 10%
Post-Entry	0.658***	0.114	0.306	0.727***	0.738***	0.517	0.845**
	(0.194)	(0.358)	(0.326)	(0.227)	(0.257)	(0.320)	(0.364)
Population (logged)	0.882**	0.164	0.099	0.820	0.545*	0.992	1.066
	(0.387)	(0.788)	(0.824)	(0.551)	(0.531)	(0.694)	(1.005)
County FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
Obs	1890	1764	1134	1680	1680	1281	966
Group	90	84	54	80	80	61	46
Log Likelihood	-1540.10	-2665.35	-1354.32	-688.72	-835.35	-589.46	-326.95

Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All regressions weighted by propensity score matching weights

Table 5: Patents and Quality; Aircraft Manufacturer

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Count of Patents With Forward Citations that Fall Into The:			
Dependent Variable	Aircraft Patents	Avg. Citations Per Patent	Standard Dev. of Citations	Bottom 10%	Bottom 25%	Top 25%	Top 10%
Post-Entry* Incumbent Aircraft Manufacturer	0.699***	0.230	0.192	0.704***	0.609***	0.699**	0.668*
	(0.178)	(0.336)	(0.342)	(0.205)	(0.194)	(0.300)	(0.356)
Post-Entry* Non-Incumbent	0.571*	-0.005	0.619	0.773**	0.995**	0.035	0.927**
	(0.310)	(0.439)	(0.473)	(0.375)	(0.437)	(0.610)	(0.432)
Population (logged)	(0.394)	(0.794)	(0.805)	(0.565)	(0.503)	(0.740)	(1.100)
F-Test (P-value)	0.27 (0.60)	0.51 (0.48)	0.71 (0.40)	0.04 (0.84)	1.03 (0.31)	1.45 (0.23)	0.53 (0.47)
County FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
Obs	1890	1764	1134	1680	1680	1281	966
Group	90	84	54	80	80	61	46
Log Likelihood	-1539.73	-2663.79	-1352.22	-688.70	-834.19	-587.60	-326.79

Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All regressions weighted by propensity score matching weights

Table 6: Patents and Quality; Higher Education

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Count of Patents With Forward Citations that Fall Into The:			
Dependent Variable	Aircraft Patents	Avg. Citations Per Patent	Standard Dev. of Citations	Bottom 10%	Bottom 25%	Top 25%	Top 10%
Post-Entry* Education High	0.695***	0.320	0.286	0.739***	0.828***	0.636**	0.886**
	(0.238)	(0.330)	(0.356)	(0.264)	(0.295)	(0.304)	(0.415)
Post-Entry* Education Low	0.583***	-0.386	0.377	0.704***	0.558**	0.261	0.773
	(0.162)	(0.493)	(0.356)	(0.240)	(0.244)	(0.725)	(0.538)
Population (logged)	0.885**	0.226	0.101	0.821	0.559	1.010	1.070
	(0.394)	(0.848)	(0.816)	(0.554)	(0.555)	(0.740)	(1.025)
F-Test (P-Value)	0.27 (0.60)	2.86 (0.09)	0.07 (0.79)	0.02 (0.89)	0.95 (0.33)	0.25 (0.62)	0.04 (0.85)
County FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
Obs	1890	1764	1134	1680	1680	1281	966
Group	90	84	54	80	80	61	46
Log Likelihood	-1539.84	-2655.72	-1354.25	-688.71	-834.79	-588.85	-326.92

Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All regressions weighted by propensity score matching weights

Table 7: Patents and Quality; Airbase

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Count of Patents With Forward Citations that Fall Into The:			
Dependent Variable	Aircraft Patents	Avg. Citations Per Patent	Standard Dev. of Citations	Bottom 10%	Bottom 25%	Top 25%	Top 10%
Post-Entry* Airbase	0.752**	-0.161	0.443	0.922**	1.028**	0.275	0.571
	(0.298)	(0.449)	(0.406)	(0.369)	(0.421)	(0.558)	(0.474)
Post-Entry* No Airbase	0.586***	0.360	0.178	0.639***	0.587***	0.749***	1.192***
	(0.175)	(0.336)	(0.362)	(0.211)	(0.194)	(0.236)	(0.342)
Population (logged)	0.821*	0.379	-0.013	0.671	0.348	1.128	1.150
	(0.446)	(0.835)	(0.909)	(0.681)	(0.678)	(0.734)	(0.911)
F-Test (P-Value)	0.32 (0.57)	1.87 (0.17)	0.44 (0.51)	0.68 (0.41)	1.32 (0.25)	0.72 (0.40)	2.01 (0.16)
County FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
Obs	1890	1764	1134	1680	1680	1281	966
Group	90	84	54	80	80	61	46
Log Likelihood	-1539.50	-2659.40	-1353.52	-688.28	-833.91	-588.43	-326.12

Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All regressions weighted by propensity score matching weights

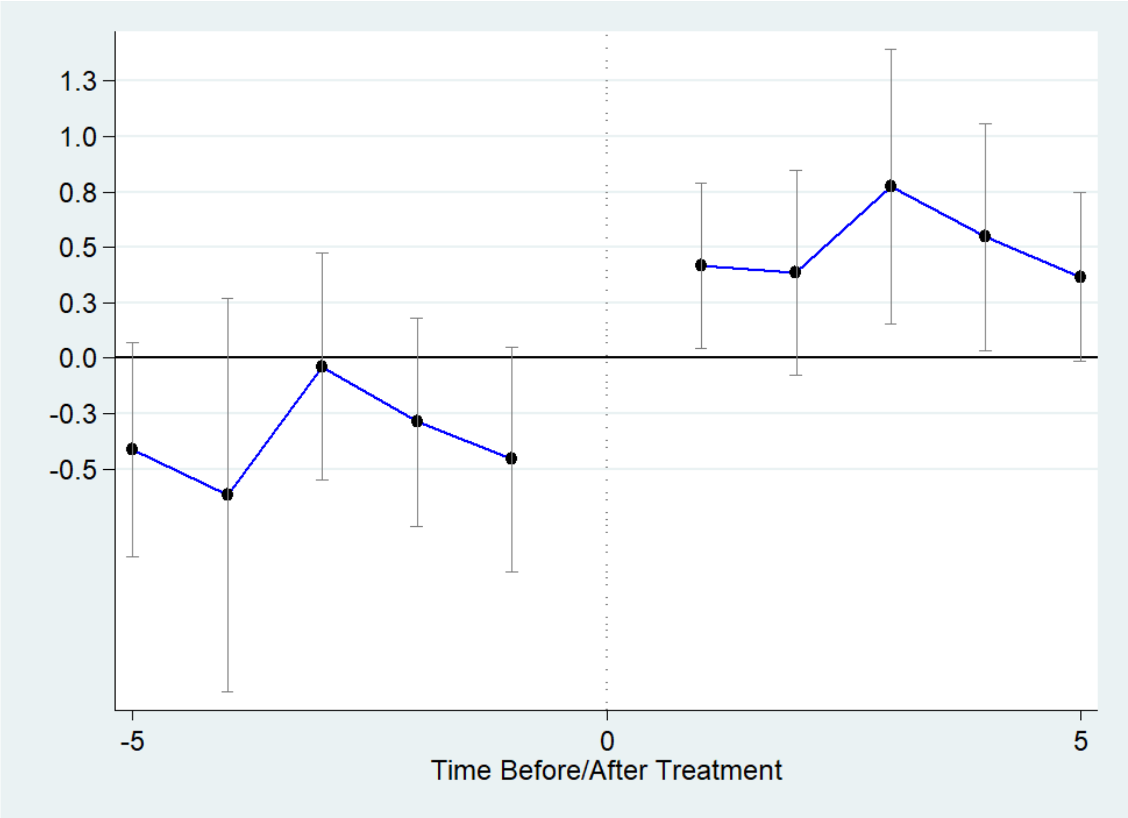
Table 8: Patents and Quality; Share of Mechanical Patents

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Count of Patents With Forward Citations that Fall Into The:			
Dependent Variable	Aircraft Patents	Avg. Citations Per Patent	Standard Dev. of Citations	Bottom 10%	Bottom 25%	Top 25%	Top 10%
Post-Entry* Mechanical High	0.586***	0.353	0.039	0.710***	0.645***	0.341	0.704
	(0.167)	(0.336)	(0.336)	(0.217)	(0.202)	(0.379)	(0.441)
Post-Entry* Mechanical Low	0.822**	-0.293	0.856***	0.771	0.950*	0.945***	1.139***
	(0.389)	(0.454)	(0.318)	(0.503)	(0.555)	(0.303)	(0.673)
Population (logged)	0.959***	0.078	0.395	0.843	0.658	1.189*	1.240
	(0.354)	(0.824)	(0.768)	(0.566)	(0.509)	(0.673)	(0.999)
F-Test (P-value)	2.46 (0.12)	0.32 (0.57)	2.39 (0.12)	0.02 (0.90)	0.43 (0.51)	1.85 (0.17)	0.68 (0.41)
County FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
Obs	1890	1764	1134	1680	1680	1281	966
Group	90	84	54	80	80	61	46
Log Likelihood	-1539.18	-2656.54	-1348.55	-688.70	-834.81	-588.25	-326.64

Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

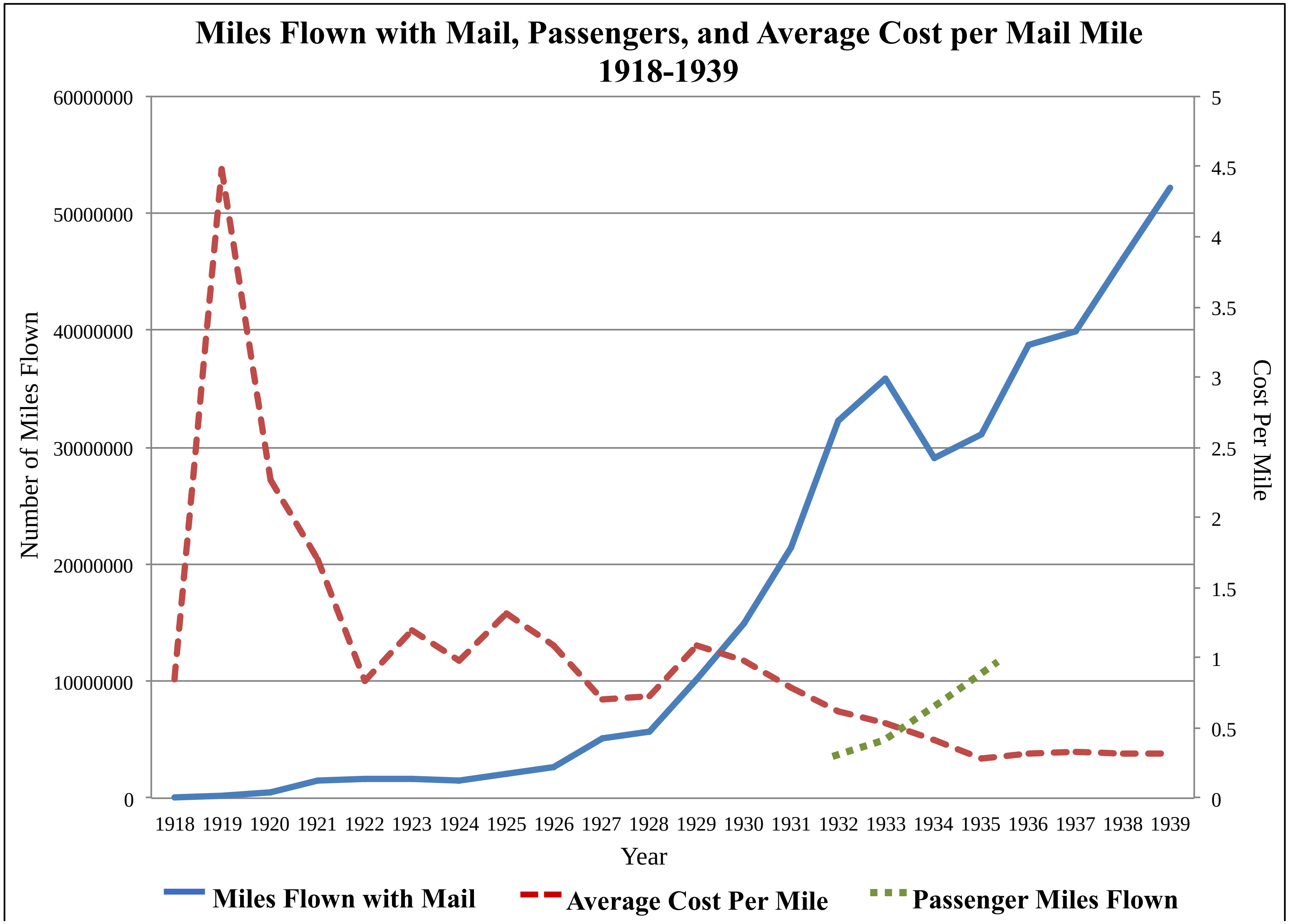
All regressions weighted by propensity score matching weights

Figure 1: 5 years pre- and post-treatment



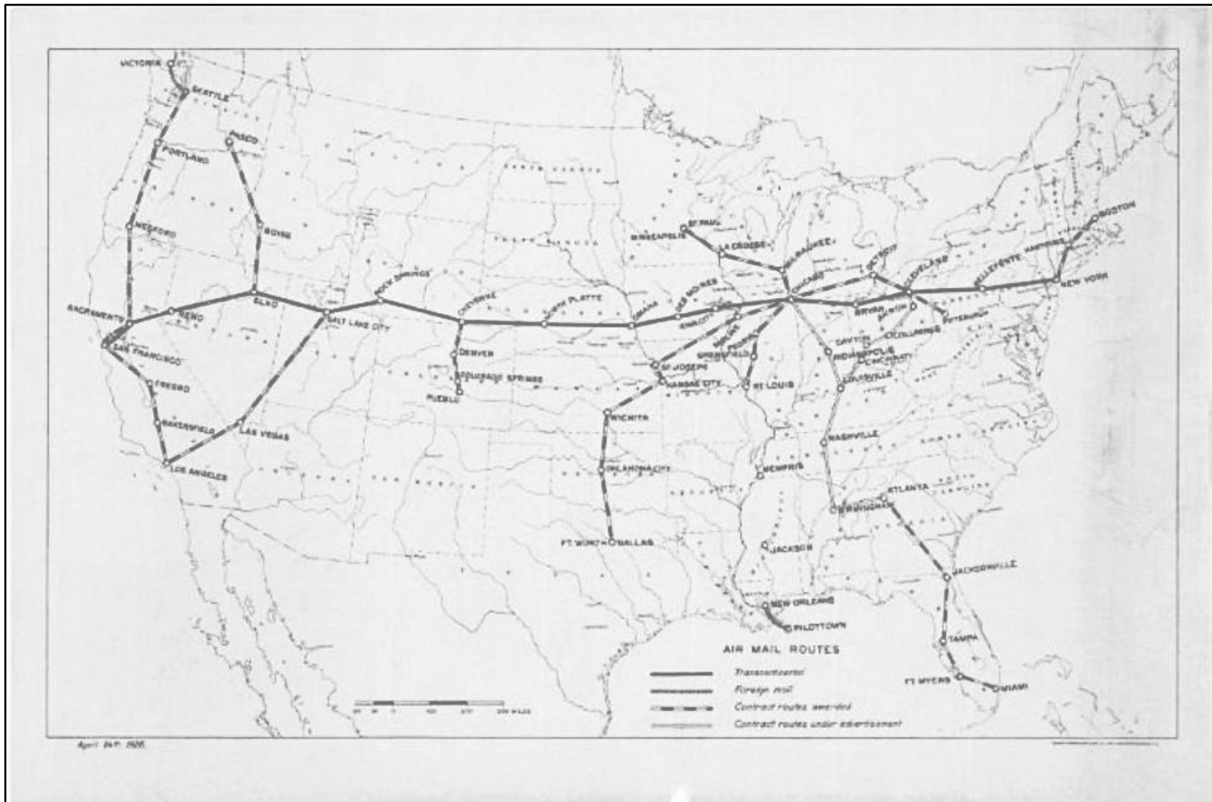
Online Appendix for
"Technological Opportunity and the Locus of Innovation:
Airmail, Aircraft, and Local Capabilities"

Appendix Figure 1:



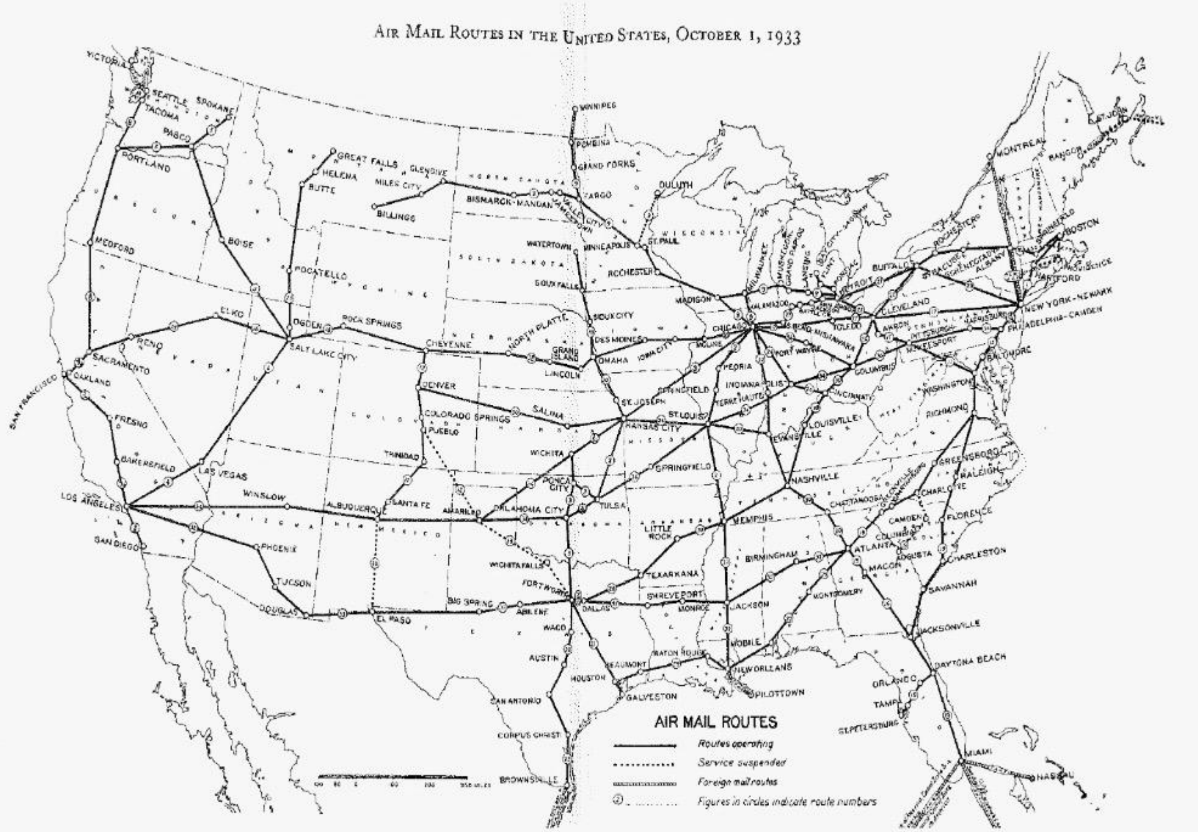
Source: various issues of the Annual Report of the Postmaster General.

Appendix Figure 2:



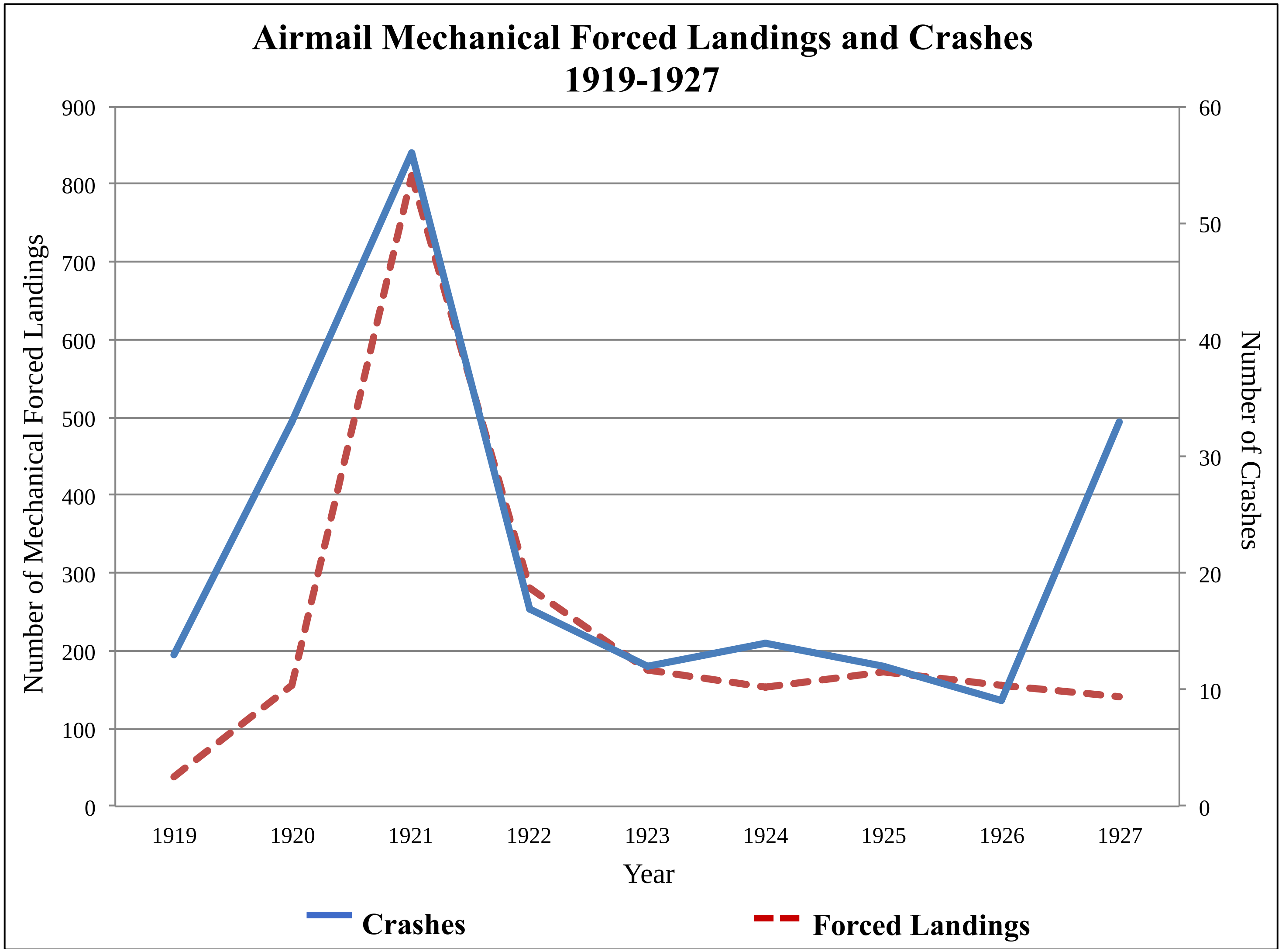
Post Office Department map of air mail routes, 04/24/1926.

Appendix Figure 3:

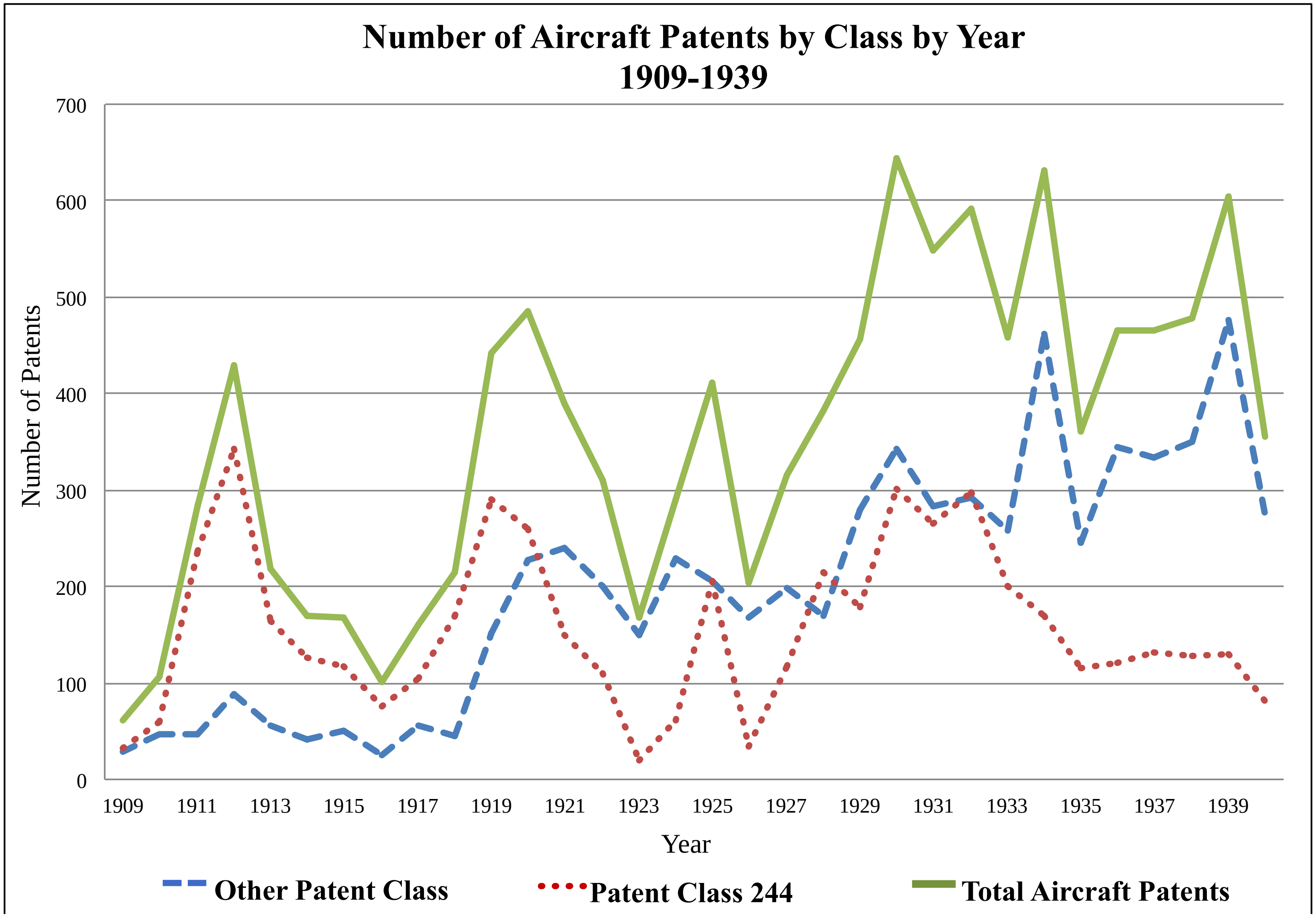


Paul T. David. 1934. *Economics of Air Mail Transportation*. Washington, D. C. The Brookings Institution

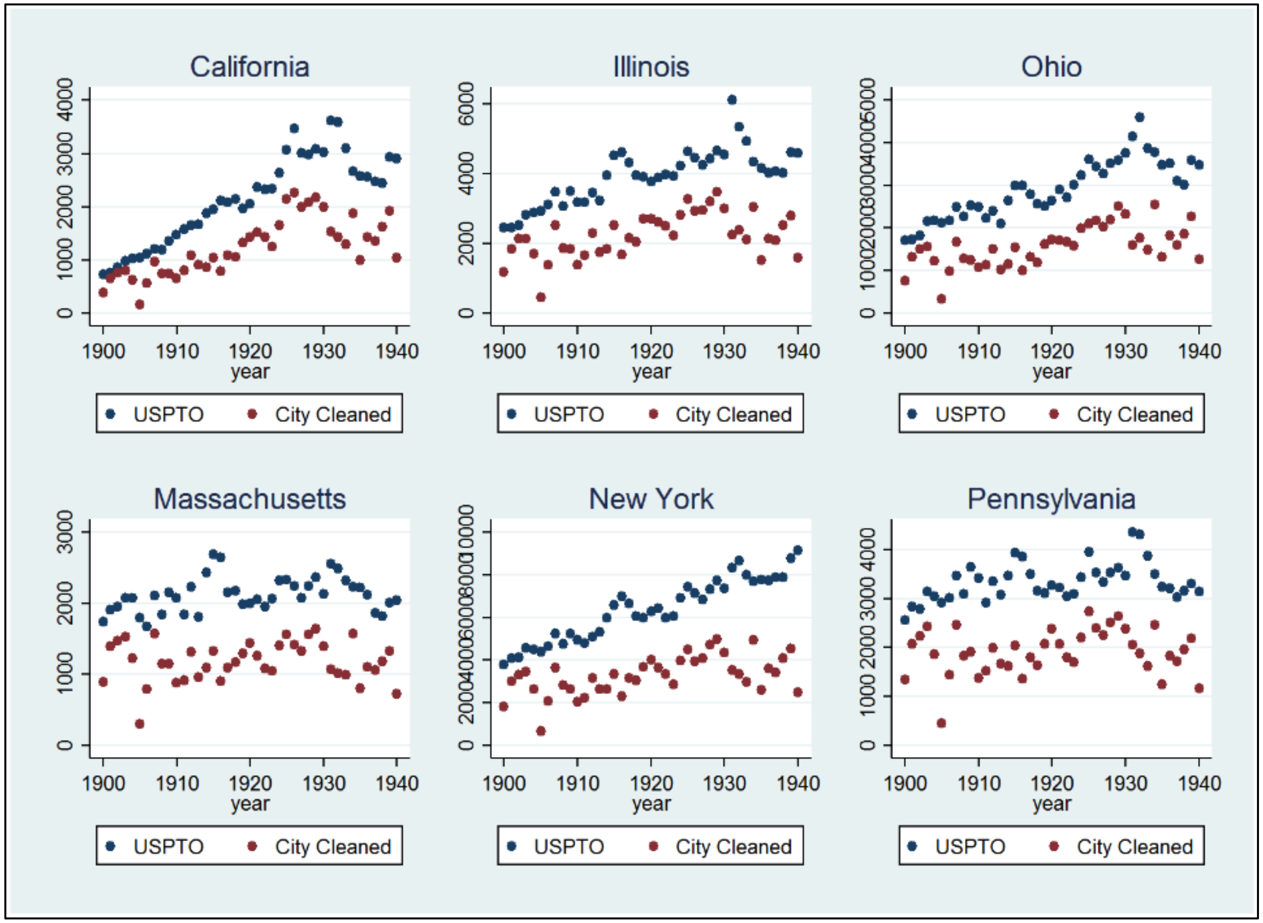
Appendix Figure 4:



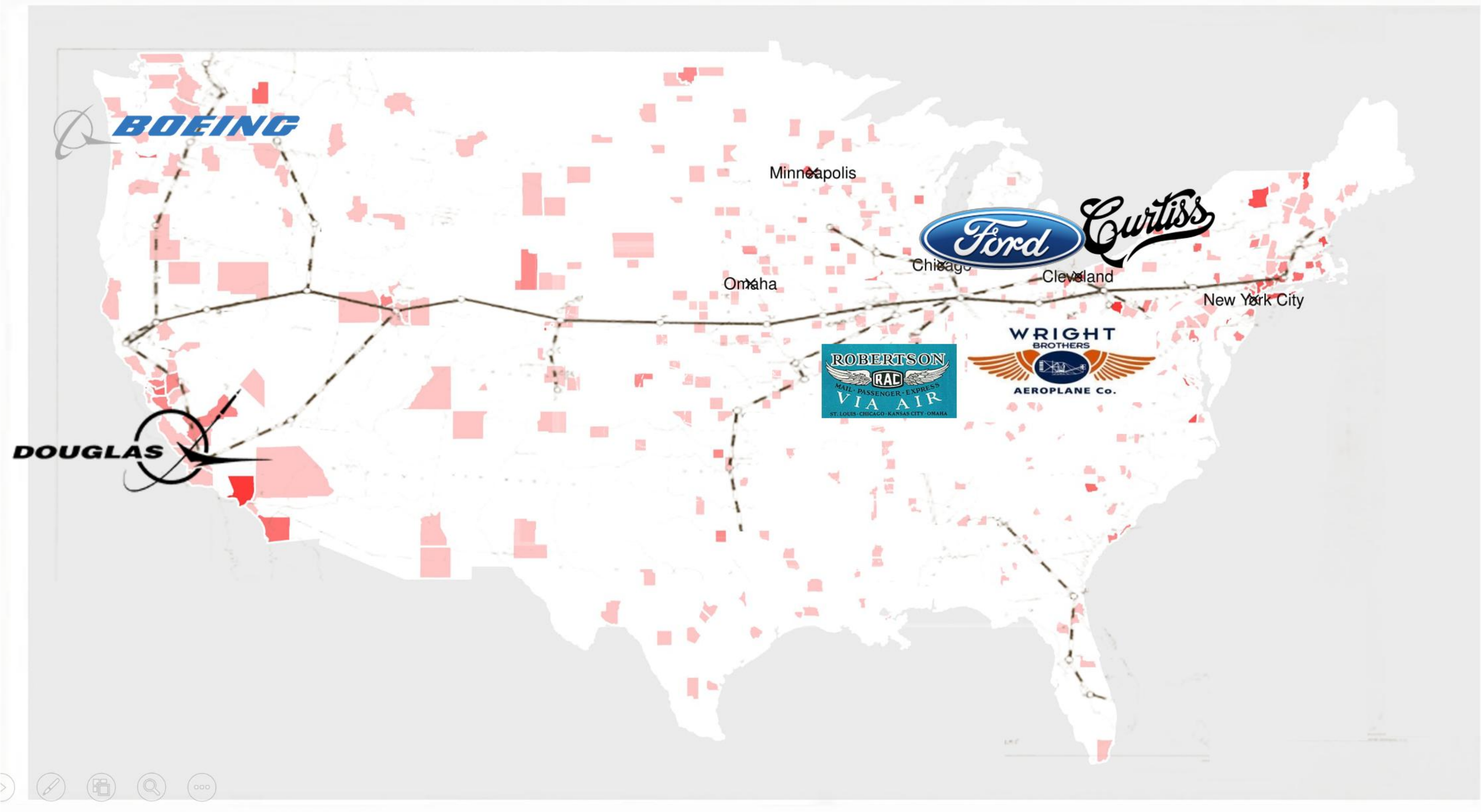
Appendix Figure 5:



Appendix Figure 6:



Appendix Figure 7: Distribution of Pre-1918 Aircraft Patents and Examples of Early Aircraft Manufacturers



Appendix Table 1. Logit Regression of Airmail Route Selection

	DV: Route Selection	
Early Manufacturer	-0.145	-0.175
	(0.445)	(0.442)
Air Base	1.555	1.481
	(0.422)***	(0.418)***
Ln(Population)	1.198	1.193
	(0.378)***	(0.370)***
Ln(Manufacturing)	0.176	0.094
	(0.298)	(0.297)
Ln(Pre-1918 Non-air Patents)		0.078
		(0.153)
Ln(Pre-1918 Aircraft Patents)		0.288
		(0.513)
Year 1918	15.008	13.644
	(0.744)***	(0.908)***
Year 1919	14.055	12.675
	(0.923)***	(1.093)***
Year 1920	15.044	13.724
	(0.754)***	(0.933)***
Year 1925	15.752	14.426
	(0.709)***	(0.939)***
Year 1926	15.766	14.449
	(0.738)***	(0.930)***
Year 1927	15.430	14.131
	(0.775)***	(0.955)***
Year 1928	15.441	14.139
	(0.717)***	(0.937)***
Year 1929	13.632	12.356
	(1.284)***	(1.432)***
Year 1930	14.329	13.044
	(0.922)***	(1.054)***
Obs	29,432	29,432
Log Likelihood	-227.23	-226.61

Appendix Table 2: Treatment and Control County List Ordered by Quartile of 1920 Population

	Treated		Control	
	County	*State*	*County*	*State*
Quartile 1	Bannock	ID	Keokuk	IA
	Elko	NV	Clark	KS
	Franklin	WA	Lancaster	VA
	Cameron	TX	Sumter	FL
	Webb	TX	Marion	IL
	Cascade	MT	Bienville	LA
			Vermillion	IN
			Greene	AR
			Otsego	MI
			Tuscaloosa	AL
			Effingham	GA
			Goochland	CA
			Wise	CA
			Yazoo	MS
			Cheyenne	NE
			Champaign	IL
			Monroe	WI
			Carroll	MS
			Comanche	KS
			Franklin	MA
			Marion	OR
			Macomb	MI
			Hillsdale	MI
			Contra Costa	CA
Quartile 2	El Paso	TX	Rensselaer	NY
	Bay	MI	Belmont	OH
	San Diego	CA	Winnebago	IL
	Pueblo	CO	Vanderburgh	IN
			Sacramento	CA
			Montgomery	AL
			Mecklenburg	NC
			Suffolk	NY
			Cumberland	PA
			Macon	IL
			Vermilion	IL
			Muskingum	OH
			Lorain	OH
			New London	CT
			Travis	TX
			Pulaski	AR
			Richland	SC
			Rock Island	IL
			Sangamon	IL
			Oklahoma	OK
			Wichita	TX
			Knox	TN
			McDowell	WV
			McLennan	TX
			Charleston	SC
Quartile 3	Kent	MI	Berks	PA
	Spokane	WA	Harris	TX
	Fulton	GA	Dauphin	PA
	Richmond	NY	Montgomery	OH
	Bexar	TX	Bergen	NJ
	Middlesex	NJ	Denver	CO
	Tarrant	TX	Nassau	NY
	Albany	NY	Passaic	NJ
	Douglas	NE	Wyandotte	KS
	Dallas	TX	Hillsborough	NH
	Salt Lake	UT	Franklin	OH
			Ramsey	MN
			Fresno	CA
			Multnomah	OR
			Norfolk	MA
			Westmoreland	PA
			Union	NJ
			Genesee	MI
Quartile 4	Jefferson	AL	Westchester	NY
	Bronx	NY	Monroe	NY
	Queens	NY	Fairfield	CT
	King	WA	Worcester	MA
	Los Angles	CA	Jackson	MO
	Wayne	MI	Essex	MA
	Hamilton	OH	Middlesex	MA
	Kings	NY	Hartford	CT
	Hennepin	MN	Milwaukee	WI
	Cuyahoga	OH	Providence	RI
	Orleans	LA	Luzerne	PA
	Essex	NJ	Marion	IN
	Jefferson	KY	New Haven	CT
			Du Page	IL
			Hudson	NJ
			Erie	NY

Appendix Table 3: Treatment and Control County List Ordered by Quartile of Pre-1918 Aircraft Patents

	Treated		**Control**	
	County	*State*	*County*	*State*
Quartile 1	Bannock	ID	Bienville	LA
	Elko	NV	Franklin	MA
	Franklin	WA	Clark	KS
	Cameron	TX	Vermilion	IL
	Albany	NY	Wichita	TX
	Bay	MI	Hillsdale	MI
			Muskingum	OH
			Rensselaer	NY
			Carroll	MS
			Yazoo	MS
			Lancaster	VA
			Otsego	MI
			McDowell	WV
			Cheyenne	NE
			Du Page	IL
			Keokuk	IA
			Tuscaloosa	AL
			Knox	TN
			Comanche	KS
			Greene	AR
			Monroe	WI
			Goochland	VA
			Wise	VA
			Belmont	OH
			Vermillion	IN
			Effingham	GA
			Sumter	FL
			Marion	IL
			Travis	TX
Quartile 2	Cascade	MT	Macon	IL
	Webb	TX	Cumberland	PA
	Jefferson	KY	Vanderburgh	IN
	Fulton	GA	New London	CT
	Pueblo	CO	Montgomery	AL
	Jefferson	AL	Fresno	CA
	Douglas	NE	Richland	SC
	Orleans	LA	Marion	IN
	Kent	MI	Contra Costa	CA
	Tarrant	TX	Rock Island	IL
			Champaign	IL
			Sangamon	IL
			Mecklenburg	NC
			Winnebago	IL
			Charleston	SC
			Macomb	MI
			Sacramento	CA
			Providence	RI
			Marion	OR
			McLennan	TX
Quartile 3	El Paso	TX	Fairfield	CT
	Spokane	WA	Worcester	MA
	Bronx	NY	Berks	PA
	Dallas	TX	Oklahoma	OK
	Bexar	T	Wyandotte	KS
	Salt Lake	UT	Lorain	OH
	Richmond	NY	Dauphin	PA
			Pulaski	AR
			Harris	TX
			Franklin	OH
			Genesee	MI
			Norfolk	MA
			Hillsborough	NH
			Ramsey	MI
			Jackson	MO
			Luzerne	PA
Quartile 4	Middlesex	NJ	Union	NJ
	Hennepin	MN	Nassau	NY
	Wayne	MI	Erie	NY
	Essex	NJ	Passaic	NJ
	Queens	NY	Milwaukee	WI
	King	WA	Hartford	CT
	Hamilton	OH	Essex	MA
	Kings	NY	Westmoreland	PA
	San Diego	CA	Multnomah	OR
	Cuyahoga	OH	Montgomery	OH
	Los Angeles	CA	New Haven	CT
			Hudson	NJ
			Monroe	NY
			Westchester	NY
			Middlesex	MA
			Suffolk	NY
			Bergen	NJ
			Denver	CO

Appendix Table 4: List of Treated Counties and Their Features

County	State	Manufacturing	High Education	Aircraft Manufacturing Corp	High Mechanical Patenting
Jefferson	AL	0	0	0	1
Los Angeles	CA	1	1	1	1
San Diego	CA	0	1	1	1
Pueblo	CO	0	1	0	1
Fulton	GA	0	0	0	0
Bannock	ID	0	0	0	0
Jefferson	KY	0	0	0	0
Orleans	LA	0	0	0	0
Bay	MI	0	0	0	1
Kent	MI	0	1	0	1
Wayne	MI	1	0	0	1
Hennepin	MN	0	1	0	1
Cascade	MT	0	1	0	1
Douglas	NE	0	1	1	1
Elko	NV	0	0	0	0
Essex	NJ	1	1	1	0
Middlesex	NJ	1	1	0	0
Albany	NY	0	0	0	0
Bronx	NY	1	0	1	0
Kings	NY	1	0	1	1
Queens	NY	1	0	1	0
Richmond	NY	1	0	1	0
Cuyahoga	OH	1	1	0	1
Hamilton	OH	1	1	0	1
Bexar	TX	0	0	1	1
Cameron	TX	0	0	0	1
Dallas	TX	0	1	1	0
El Paso	TX	0	0	0	1
Tarrant	TX	0	1	1	0
Webb	TX	0	0	0	1
Salt Lake	TX	0	1	0	1
Franklin	WA	0	0	0	1
King	WA	1	1	0	1
Spokane	WA	0	1	0	1

Appendix Table 5: Main Result Using Conditional Fixed Effects Negative Binomial

	(1)	(2)	(3)	(4)
	Aircraft Patents 1915-1935	Aircraft Patents 1915-1935	Aircraft Patents 1915-1930	Aircraft Patents Treated Counties Only 1915-1935
Post-Entry	0.499***	0.406***	0.542***	0.402***
	(0.128)	(0.124)	(0.135)	(0.155)
Population (logged)		0.655***	0.819***	0.760***
		(0.137)	(0.166)	(0.197)
County FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Obs	1890	1890	1424	630
Group	90	90	89	30
Log Likelihood	-1320.67	-1309.69	-946.60	-635.49

Standard errors in parentheses, clustered by county

All regressions weighted by propensity score matching weights

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Appendix Table 6: Treated Counties Defined with Stricter Cut-offs

	(1)	(2)	(3)	(4)	(5)
	Aircraft Patents 1915-1935	Aircraft Patents 1915-1935	Aircraft Patents 1915-1930	Aircraft Patents Treated Counties Only 1915-1935	Non-Aircraft Patents 1915-1935
Post-Entry	0.556**	0.472*	0.566**	0.700***	-0.012
	(0.270)	(0.280)	(0.278)	(0.192)	(0.078)
Population		0.690*	1.477***	0.640	0.780***
(logged)		(0.399)	(0.505)	(0.454)	(0.167)
County FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
Obs	1911	1911	1440	609	2415
Group	91	91	90	29	115
Log Likelihood	-1264.11	-1258.70	-898.05	-591.94	-6359.78

Treated counties with pre-1918 stock of non-aircraft patents greater than 5,000 were dropped
Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
All regressions include propensity score matching weights

Appendix Table 7: Treated Counties Without Cut-offs

	(1)	(2)	(3)	(4)	(5)
	Aircraft Patents 1915-1935	Aircraft Patents 1915-1935	Aircraft Patents 1915-1930	Aircraft Patents Treated Counties Only 1915-1935	Non-Aircraft Patents 1915-1930
Post-Entry	0.349**	0.350**	0.448***	0.251	0.014
	(0.154)	(0.154)	(0.156)	(0.158)	(0.055)
Population		-0.039	0.568	0.087	0.295**
(logged)		(0.235)	(0.414)	(0.167)	(0.137)
County FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
Obs	2373	2373	1808	840	2856
Group	113	113	113	40	136
Log Likelihood	-2219.99	-2219.87	-1630.82	-994.55	-9345.42

Standard errors in parentheses, clustered by county; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

All regressions include propensity score matching weights