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Breakthrough innovations in aircraft and the intellectual property system, 1900-1975

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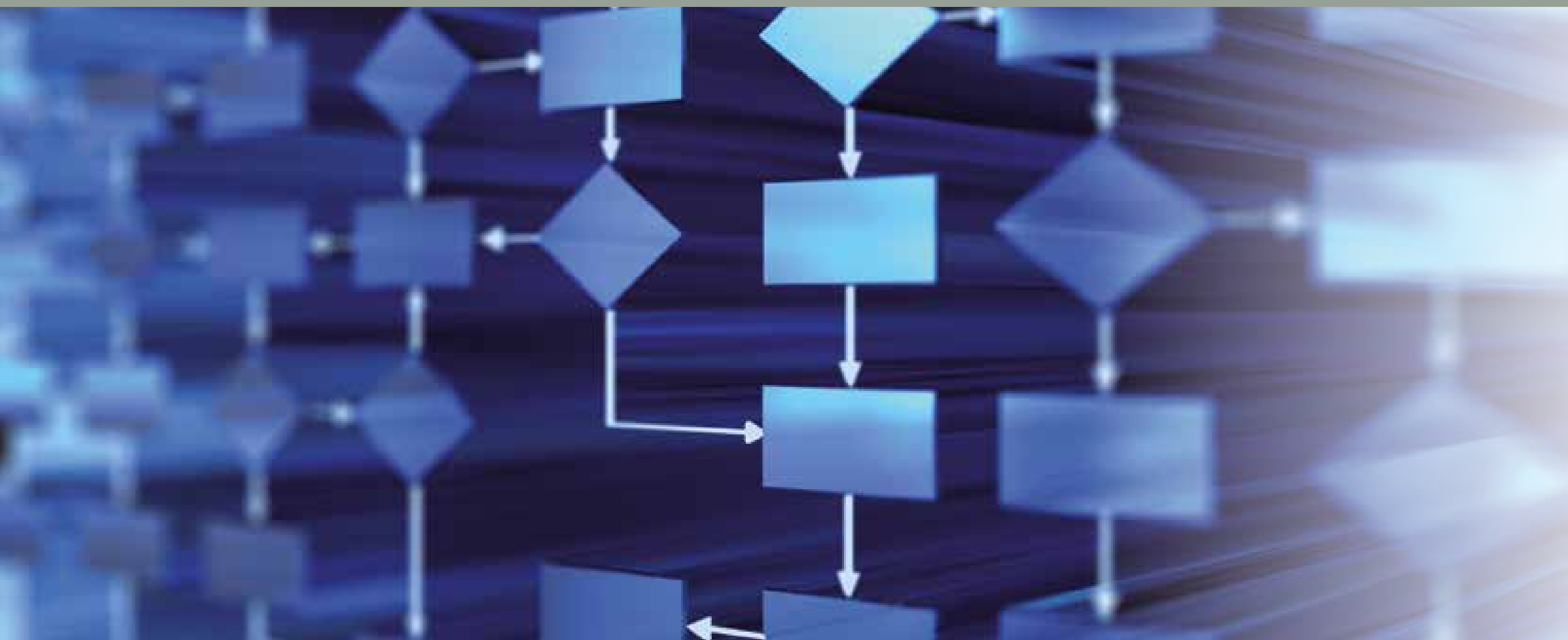

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Abstract:

Modern commercial aircraft are complex products that incorporate innovations in technologies ranging from advanced materials to software and electronics. Although commercial aircraft assuredly qualify as a transformative innovation, in fact today's commercial aircraft are the result of a process of incremental innovation and improvement that dates back more than a century. A great many of these improvements and incremental innovations originated from government-supported R&D programs sponsored by the military services or government research laboratories. The adoption of commercial-aircraft innovations within many industrial economies, including the United States, also has been influenced by government regulation of air transportation.

This paper provides a historical characterization of the innovation and record of technical progress in US commercial aircraft during the 1900-1975 period. It identifies the sources of support for innovation and technological adoption, and examines the origins and impacts of "breakthrough innovations" on the overall evolution of the global commercial aircraft industry. The paper also assesses the role of patents in these important innovations.

Keywords: Innovation, airplane, intellectual property

JEL Codes: O3, O34, O380, N7

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I. Introduction

Modern commercial aircraft are complex products that incorporate innovations in technologies ranging from advanced materials to software and electronics. Although commercial aircraft assuredly qualify as a transformative innovation, in fact today's commercial aircraft are the result of a process of incremental innovation and improvement that dates back more than a century. A great many of these improvements and incremental innovations originated from government-supported R&D programs sponsored by the military services or government research laboratories. The adoption of commercial-aircraft innovations within many industrial economies, including the United States, also has been influenced by government regulation of air transportation.

Although patents originally assigned to the Wright Brothers covered broad elements of aircraft design and were the focus of litigation immediately before World War I, pressure from the U.S. armed services led to the formation of a patent pool governing the licensing of these and other patents. The Manufacturers' Aircraft Association operated from 1917 until 1975, when the U.S. Justice Department negotiated its demise. The unusual elements of this patent pool notwithstanding, there is little evidence that formal intellectual property rights exercised a strong influence on the pace of innovation or the evolution of market structure in the global commercial aircraft industry. The progressive exit of producers of airframes and engines since the 1960s, as well as the lack of entry by firms based outside of the United States or Europe during this period, do not appear to be linked to the power of patents or other formal IP instruments. Instead, the progressive consolidation of the global commercial aircraft industry reflects the changing relationship between military and commercial aircraft technologies and the rising risks and costs of new product development in commercial aircraft. Indeed, the widespread use by leading U.S. and European producers of "strategic alliances" with firms in other nations reflects the efforts of these established producers to tap new sources of finance for new-product development as well as the ability of such alliances to facilitate access to markets for commercial aircraft and engines. In contrast to other high-technology sectors such as pharmaceuticals, aircraft-industry collaborations among firms do not appear to be vehicles for licenses covering other firms' intellectual property.

This paper begins with an overview of the characteristics of innovation and the record of technical progress in commercial aircraft during the 1920-75 period, reflecting the fact that a commercial aircraft "industry" scarcely existed before World War I. I follow this discussion with a summary of the sources of support for innovation and technological adoption in the U.S. commercial aircraft industry, one that dominated global markets for airliners for much of the 1920-75 period. A section examining the origins and impacts of "breakthrough innovations" that spans the 1903-75 period (thereby including the Wright brothers' seminal innovation and its complicated patent history) is next, and is followed by an assessment of the role of patents in these important innovations and the overall evolution of the global commercial aircraft industry. International diffusion of commercial aircraft is discussed in the next section, followed by concluding remarks.

II. Characteristics of commercial-aircraft innovation

The links between innovation in commercial aircraft and technological developments in a wide range of other industries reflects the fact that a given aircraft or engine design integrates a number of complex subsystems, involving electronics, hydraulics, and materials technologies. The interaction of these individually complex systems or components is crucial to the performance of an aircraft design, yet often is difficult to predict. Considerable technological uncertainty thus pervades the development of a new airframe or engine design, rendering the systems integration and design phases critical to the introduction of a successful new product. As I note below, such technological uncertainty has played a critical role in the introduction of several “breakthrough innovations,” including the first jet-powered commercial airliner.

The dynamic character of the market and of commercial aircraft technology contributes to the length of the design phase in aircraft innovation. In an effort to accommodate the broadest possible group of purchasers, major firms produce dozens of “paper airplanes” prior to the decision to launch the development of a design. Former Boeing vice president John Steiner cited

> The excruciating pain of trying to achieve a common denominator among varying airline requirements. All commercial programs go through a similar process and the engineers must work with a great many airlines, not just the few who are most likely to become launch customers. (Steiner, 1982)

In the design of the Boeing 727 (a program headed by Steiner), this process took two and one-half years and produced at least nine separate designs for the aircraft. The design definition phase for the Boeing 767 lasted nearly six years. Once a producer decides to introduce a new aircraft design, however, speed in reaching the market is essential.

Another reason for the importance of product design in this industry is the fact that an aircraft design is produced for a remarkably long time. The Boeing 727 was produced for 20 years, the manufacture of the DC-8 extended from 1957 through 1972, and the Boeing 747 has been manufactured for 45 years. While these aircraft were produced over lengthy periods, their designs were modified in major ways, not least through “stretching” the fuselage to accommodate additional passengers, or retrofitting an airframe with new engines. Other incremental modifications are made throughout the life of a given airframe design or engine. Such changes rely heavily on information gained from close monitoring of operating experience after the introduction of an aircraft. The importance of this monitoring function and of product support (spare parts supply and field service) makes the establishment or existence of a global marketing and product support organization critical to market acceptance of a new aircraft design. The cost and time required to build up such a global product support network is a significant barrier to entry into the modern large (greater than 100 passengers) commercial aircraft industry.

Another source of entry barriers is the high and growing cost of new product development. Development costs increased (in constant dollars) at an average annual rate of nearly 20 percent during 1930-70, considerably greater than the average annual rate of growth in aircraft weight of 8.5 percent. Development of the Douglas DC-3 in the 1930s cost roughly $3 million (Miller and Sawers, 1968). The DC-8, introduced in 1958, cost nearly $112 million to develop, while development of the Boeing 747, production of which began in the early 1970s, cost nearly $2 billion. Development costs have continued to grow to more than $20 billion for the most recent generation of commercial aircraft such as the Boeing 787 and Airbus 380. Such growth in development costs means that an increasing portion of the costs of introducing a new aircraft is incurred during the phase of greatest uncertainty concerning market prospects and technical feasibility.

A final dimension of production-cost behavior in airframes is reductions in variable costs as a function of cumulative production volume—the well-known learning curve, first documented in the manufacture of airframes during World War II. Cost reduction over the course of an airframe’s production history is dramatic—most estimates suggest that a doubling of output reduces unit costs by as much as 20 percent. The potential for such cost reduction as a function of cumulative production volume provides another motive for stretching an airframe design, since a stretched airframe can capture further cost-reducing benefits from movement down the learning curve.

III. The record of technical progress in commercial aircraft, 1925-75

A. Measures of technical progress in commercial aircraft

Since the U.S. commercial air transportation industry is the primary beneficiary of technical progress in commercial aircraft, one index of the cumulative effects of innovation in commercial aircraft is the growth of productivity in air transportation. Total factor productivity in U.S. air transportation grew at an average annual rate of 8 percent during 1948-66, a higher growth rate than in almost any other U.S. industry during this period (Kendrick, 1961). Fraumeni and Jorgenson (1980) similarly concluded that total factor productivity growth in U.S. air transportation was exceeded only by that in telecommunications during 1948-76. This record of high productivity growth reflects more than innovation in commercial aircraft alone. Air traffic control improvements, innovations in ground-based navigational equipment, airfield expansion and modernization and other enhancements in the overall domestic and international air transportation infrastructure, many of which were financed by governments (in the United States, the Federal Aviation Administration), have been of great importance.

Other indicators of technical progress in commercial aircraft focus solely on improvements in aircraft performance. One measure of aircraft performance that is available for new aircraft designs over a relatively lengthy time period is passenger capacity (seats) multiplied by cruising speed, $AS*V_c$. Figures 1 - 3 depict the evolution of aircraft performance using this measure for a sample of piston- and jet-powered commercial aircraft respectively for the entirety of the 1925 – 1975 period, 1925-40, and 1945-75. The use of separate Figures to depict change in this measure of technical progress before and after World War II (during which the commercial aircraft industry essentially ceased operations) reflects the remarkable growth in $AS*V_c$—the 1920s and 1930s in Figure 1 are scarcely legible because of the dramatic magnitude of the increase in this measure across five decades. Figures 3 – 6 for the same periods show trends in cruising speed, highlighting the significant improvement in cruise speed made possible by the introduction of the jet engine in the early 1950s, as well as the relative stability in average cruise speed for commercial jet aircraft following the introduction of the jet engine. Improvements in commercial aircraft performance since the 1950s have relied more on growth in passenger capacity rather than increased speed. Passenger capacity growth has required more than technical progress in commercial aircraft alone, inasmuch as the logistics for boarding and deplaning hundreds of commercial passengers have placed new demands on airport infrastructure and other components of the commercial air-transportation systems of the United States and other nations.

Another measure of commercial aircraft performance that is less complete but still revealing is trends in direct operating costs per seat-mile for the 1925 – 75 period (Figure 7). The data in Figure 7 highlight the sharp drop in operating costs made possible by the DC-3, introduced in the 1930s. Another significant drop in seat-mile costs, attributable to improved fuel economy and expanded passenger capacity, occurred with the introduction of the wide-body transports (the Boeing 747, Lockheed L-1011, and McDonnell Douglas DC-10) that employed high-bypass turbofan engines (see below for a discussion of high-bypass turbofan engines as a "breakthrough innovation"). According to Rosenberg et al. (1978), costs per seat mile declined tenfold between the introduction of the monocoque airframe in 1933 and the introduction of the 747 in 1970, while $AS*V_c$ rose by a factor of 20 during the same period.

Still another measure of the economic benefits of technical progress in commercial aircraft estimates the resource savings associated with improved commercial aircraft performance (Mowery, 1985). A calculation of the "social savings" associated with technical progress compares the operating costs of the 1983 volume of U.S. domestic commercial air travel using the 1983 aircraft fleet with the costs that would be realized through the exclusive use of DC-3s in that service. The comparison of an "all-DC-3" fleet with the 1983 fleet is fairly conservative, inasmuch as the DC-3 exhibited much lower operating costs than its commercial contemporaries. Moreover, by 1939, the base year for this comparison, the operating costs of the DC-3 had declined somewhat from those associated with the early

years of this aircraft's service. In 1983, on the other hand, both the Boeing 757 and 767 were still relatively new and therefore should have displayed operating costs somewhat above their long-run averages.
The substitution of the 21-seat DC-3 for the current fleet of larger commercial aircraft also would produce gridlock at the nation's airports because of the huge increase in flights, landings and takeoffs needed to transport 1983 passenger volumes. The higher costs of transporting the larger passenger volumes of 1983 in DC-3 aircraft also would translate into higher ticket prices, depressing passenger volume somewhat. These calculations thus are purely illustrative rather than definitive, but they suggest that transporting 1983 passenger volumes with 1939-vintage DC-3s would cost nearly $18 billion (1972 dollars) more than the actual 1983 costs of domestic air transportation of $5.8 billion (1972 dollars). This measure of technical progress indicates that technical progress in commercial aircraft saved more than 75 percent of the costs of achieving 1983 passenger volumes with the most modern and innovative 1939-vintage equipment.

B. The importance of "beta-phase" incremental innovation in commercial aircraft

The impressive gains in operating efficiency that have contributed to these social savings and economic benefits are largely attributable to sustained incremental innovation. Data on the technical performance of commercial aircraft repeatedly highlight the significant performance improvements during the life of a given aircraft design, reflecting incremental improvements in engines, airframes, and operations. For a number of aircraft, these "intra-generational" performance gains exceed the "intergenerational" advances associated with the introduction of "breakthrough innovations" in aircraft.

One useful conceptual approach to understanding this type of intra-generational performance improvement in commercial aircraft in particular is Enos's (1962) distinction between the "alpha" and "beta" phases of a new technology's operating history. The alpha phase may be described as the period of inventive activity for a particular technology that precedes its introduction to the market, whereas the "beta" phase refers to the process of incremental technological change that occurs after a technology is in operation. Innovation in commercial aircraft combines significant performance advances from both phases of the innovation process, although the "beta" phase arguably has been especially significant within "design generations" of commercial aircraft (two-engine piston powered aircraft; four-engine piston powered aircraft; the first generation of jet-powered aircraft; and wide body aircraft powered by high-bypass turbofans). From 1933 to 1956, for example, costs per passenger seat-mile for two-engine commercial aircraft (defined here as a single "generation" of airframe designs) declined from US$.075 to US$.022, while productivity ($AS*V_c$) rose from 1800 to 14,600 during the same period. For another single "generation," four-engine piston airliners, operating costs dropped from US$.0322 in 1940 to US$.018 in 1953, nearly 50%, while $AS*V_c$ grew from 9400 to 25,000 and cruising speed increased from 200 to 300 mph. Between 1960 and 1965, operating costs for the four-engine jets represented by the DC-8 and Boeing 707 decreased from roughly US$.017 to US$.0115.
The intra-generational gains in productivity and reductions in operating costs associated with the "beta phase" in both two- and four-engine piston commercial aircraft exceed the gains associated with the introduction of the first models of these aircraft (respectively, the two-engine Boeing 247 and the four-engine Boeing 307). The Boeing 247, for example, experienced declines in seat-mile operating costs of roughly 6.1% per year during 1933-40, while the Lockheed Electra (an advanced four-engine commercial airliner of the same generation as the Boeing 307) experienced reductions in operating costs that averaged 7% per year during 1960-65. These intra-generational improvements in performance reflect the design and construction of larger airframes, adoption of new component technologies developed in other industries, and improved operating efficiency.

In the case of the DC-8, seat-mile operating costs dropped by more than 50% and AS*Vc more than doubled through the design modifications that replaced the early DC8-10 with the DC8-30 and -50. These operating-cost reductions reflected improvements in the aircraft's engines that increased their available thrust and reduced fuel consumption, as well as complementary modifications in the aircraft's wing profile that reduced drag. But perhaps the most important modification in the design of the DC-8 was the "stretch" of the aircraft's fuselage that increased passenger capacity from 123 to 251 seats. The incremental modifications in the design of the DC-8 that cumulatively resulted in dramatic improvements in operating efficiency were highly interdependent—stretching the fuselage required improvements in engine thrust that did not incur significant fuel consumption penalties, while both fuselage stretching and the use of improved engines required complementary improvements in wing design. Advances in engines and wing designs also were facilitated by innovations in related industries, such as new materials and aviation fuels.

The third source of intra-generational performance improvements in commercial aircraft is through "learning by using" the new technology. One of the clearest examples of such "learning by using" is in maintenance, which can account for as much as 30% of the direct operating costs of aircraft. In the case of jet engines, maintenance operations were initially based on experience with piston-powered engines, which required frequent maintenance overhauls.[2] Moreover, the first applications of jet engines occurred in military aircraft, where cost considerations were of limited importance relative to performance and relatively little attention was devoted to improving the efficiency and cost-effectiveness of maintenance activities. Accumulated experience with civilian operation of jet engines during the 1950s, however, resulted in new approaches to engine maintenance that reduced operating expenses for both civilian and military jet engines. The trends depicted in Figure 8 for the JT3-D turbojet that was employed on the Boeing 707 and Douglas DC-8 illustrate the significant reductions in maintenance expenses over the operating life of this new technology. Operating experience also influenced modifications in the design of jet engines, as reduced requirements for comprehensive reconditioning of the entire engine resulted in an effort to redesign engines to accommodate maintenance as needed of specific modules of the overall engine. Improvements in monitoring equipment and diagnostics have further reduced maintenance costs.

The knowledge flowing from the incremental innovation associated with "beta-phase" improvements in efficiency is rarely patented or patentable. In many cases, as in the gains in maintenance efficiency, this knowledge is embedded in an organization and may or may not be easily imitated by others. In other cases, such as the performance gains associated with fuselage "stretching" or the addition of new engines to an airframe, the innovations are based as much on cautious extension of operation or design practices, and as such are subject to considerable uncertainty and risk.

IV. Sources of innovation in U.S. commercial aircraft: R&D investment, 1945 - 82

Another characteristic of innovation in commercial aircraft in the United States and other industrial economies is the central role of government. Throughout the 20th century, governments have influenced the commercial aircraft industry through their regulation of domestic and international passenger transport, their substantial purchases of military aircraft, and their generous support for the R&D investment and aeronautics research infrastructure that underpin innovation in both military and civilian aircraft. This section focuses on R&D investment in the U.S. aircraft industry during 1945-82, an era of quasi-mobilization for the Cold War during which the scale of U.S. government support for R&D in the U.S. aircraft industry outstripped that of other industrial economies. Nonetheless, the governments of other industrial economies played important roles in their domestic aircraft

[2] Improvements in engine maintenance procedures also produced significant efficiency gains in piston engines as well. Miller and Sawers (1968, p. 89) estimate that between 1920 and 1936, engine maintenance costs for radial reciprocating engines fell by as much as 80%.

industries that in some cases (e.g., state ownership of leading producers) exceeded the level of intervention seen in the United States.

U.S. aircraft industry R&D investment from all sources during 1945-82, the only period for which reliable data are available, amounted to nearly US$104 billion in 1972 dollars (Table 1). Of this total, almost 75 percent, US$77 billion was provided by the U.S. Department of Defense (DoD). Industry-financed R&D during the period amounted to US$17.4 billion, roughly 15 percent of the total. Federal nonmilitary R&D funding was a small portion of the total investment, totaling some US$8 billion. Although a small portion of this large federal R&D investment was carried out in public laboratories, the vast majority of these funds supported R&D in private industry—during the 1967 – 79 period, 73 – 80% of R&D performed by private firms was underwritten by federal funds. The large investment of public (especially military) funds was not intended to support innovation in commercial aircraft; national security considerations motivated the vast majority of federally funded R&D. Nevertheless, this large federal investment in military aircraft technologies had a significant impact on innovation in commercial aircraft during and after this period.

NASA R&D funding grew at a modest rate during the 1945-82 period and was essentially constant during the 1969-82 period. Although in 1945, R&D investment by NACA, NASA's predecessor agency, exceeded industry-financed R&D spending, by the mid-1950s, NACA accounted for less than 20 percent of industry-financed R&D investment. Expenditures by the U.S. Atomic Energy Commission on nuclear propulsion of aircraft and space vehicles, and the Federal Aviation Administration supported work on avionics and the supersonic transport during the 1960s.

Industry-financed research expenditures display an oscillating pattern of growth and decline during the 1945-82 period, in contrast to the pattern of growth in overall industry-financed R&D investment during this period in U.S. manufacturing. Successive waves of industry-funded investment in the development of three generations of airframes and engines during the 1945-82 period are apparent in the data in Table 1: R&D investment grew rapidly during the early 1950s, the period of development of the first commercial jet aircraft; during the late 1960s, as the wide-body transports and high-bypass engines were developed; and during the late 1970s, with the development of the succeeding generation of smaller, fuel-efficient aircraft (the Boeing 757 and 767) equipped with downsized high-bypass engines.

A. The Role of NACA and NASA

The U.S. commercial aircraft industry is virtually unique among U.S. manufacturing industries in that a federal research organization, the National Advisory Committee on Aeronautics, NACA (subsequently absorbed by the National Aeronautics and Space Administration, NASA), for many years has conducted and funded R&D on airframe and propulsion technologies of use to military and civilian applications. This section discusses the history and contributions of NACA and NASA R&D.

U.S. involvement in World War I resulted in the establishment of a number of organizations intended to bring together academic, business, and government experts to analyze important problems of national security in the areas of industrial mobilization, research, and technology development. The National Research Council (NRC, housed within the National Academy of Sciences) was one such body, and NACA was another, established as a federal advisory council in 1915. NACA was charged with supporting research on "…the scientific problems involved in flight," as well as advising "…the military air services and other aviation services of the government." During its early years, NACA worked on problems of aerodynamics and aeronautics of interest to both military and commercial sectors.

NACA facilities at Langley Field, Virginia and after 1940, at Moffett Field, California and Cleveland, Ohio, were important sources of performance and other test data in aeronautics. The committee pioneered in the construction and operation of large wind tunnels, completing one in 1927 (based on a design pioneered at the University of Gottingen in Germany) that could accommodate full-scale airframes. Test data from this and other facilities led to major improvements in airframe design, including the unpatented "NACA cowl" for radial air-cooled piston engines that reduced airframe drag by nearly 75 percent and was incorporated into the DC-3 design. NACA research also demonstrated the superior performance of airframes with retractable landing gear and led to important modifications in aircraft wings. Total appropriations for NACA for 1915-40 amounted to US$81 million in 1972 dollars, less than one-third of NASA's annual budget for aeronautics R&D in the late 1970s.

NACA also supported the inward transfer to U.S. firms and researchers of European aerodynamics research. A Paris office was established in 1919 to serve as a "listening post" for tracking European research on aircraft, and as early as 1920 NACA representatives from the Paris office were visiting German aerodynamics research facilities (Eckert, 2005). Ludwig Prandtl, a leading German researcher on aerodynamics on the faculty at Gottingen University, was commissioned in 1920 by NACA to prepare a survey of the state of advanced knowledge in the field of aerodynamics. In 1921 Max Munk, one of Prandtl's senior assistants, was hired by NACA to work at its facilities in Washington D.C. and eventually, at its Langley aeronautics laboratory.[3] Although Munk's difficult personality meant that his tenure with NACA was brief (roughly 6 years), he contributed numerous publications on airfoil design, a body of knowledge that was essential to wing design. Munk also designed and oversaw the construction of an advanced wind tunnel at the Langley Laboratory, drawing on his experience with the wind-tunnel facilities at Gottingen.

Before World War II, NACA R&D focused mainly on providing test results for both civilian and military designers, particularly in the field of wing design, building on Munk's work and utilizing its wind tunnel facilities in Virginia and California. Indeed, NACA performed little research during this period that could be described as "basic." With the onset of World War II, NACA's research focused increasingly on military aircraft design, and by 1945, the structure of the U.S. aeronautics research infrastructure had changed considerably. The major U.S. aircraft producers acquired substantial in-house R&D budgets and facilities during the war, and NACA's facilities were less essential. Military support for aircraft-

[3] As a citizen of a foreign power still technically engaged in hostilities with the United States before the ratification of the Versailles Treaty, Munk's hiring required a special order from President Woodrow Wilson (see Roland, 1985).

industry R&D expanded greatly, and NACA's importance declined. The agency remained an important sponsor of academic research in aeronautics, however, and continued to support test work on a scale that was dwarfed by military-supported R&D.

In 1958, in the wake of the Soviet launch of the Sputnik satellite, NACA was absorbed into the National Aeronautics and Space Administration, a new agency created to support space exploration. Aeronautics R&D was a small share of the new agency's overall budget and mission. In 1966, a Library of Congress prepared for the Senate Committee on Aeronautical and Space Sciences noted that "Space budget demands have probably hampered what might have been expected to be a normal growth of the level of effort in aeronautics within the agency…" (Legislative Reference Service, 1966, p. 107). In the aftermath of the Apollo program, NASA's overall budget grew more slowly, and budgetary pressures on the agency's aeronautics programs mounted. Appropriations for aeronautics R&D grew during the 1970s at a much slower rate that had been true during the 1960s, and NASA's aeronautics R&D focused less on fundamental research (National Research Council, 1982).

Although its importance within the U.S. aircraft industry's R&D activities declined after 1945, NACA and NASA played important roles throughout the postwar period in financing and managing large research facilities and supporting R&D that often involved collaboration among erstwhile competitors within the aircraft industry, potentially reducing duplicative R&D investment and activities. It is likely that NACA/NASA programs and research facilities reduced the overall costs of R&D for the U.S. aircraft industry, although credible estimates of the magnitude of any resource savings are difficult to find. A subcommittee of NASA's Advisory Committee on Aeronautics (hardly a disinterested source) suggested that if NASA aeronautics research was terminated and private airframe and engine firms individually supported one-half of the NASA research programs relevant to their segments of the industry during 1982-1991, while collaborating on 18 percent of these programs, the additional costs associated with increased duplication in industry-supported R&D would have amounted to nearly US$1 billion in 1972 dollars (NASA Aeronautics Advisory Committee, 1983).

B. Military-Sponsored R&D

The most substantial source of government support for U.S. aircraft industry innovation throughout the post-1945 era has been defense-related spending on R&D and procurement. Military sources provided the vast majority of the considerable federal R&D investment in aircraft during this period, and this investment targeted innovation in military rather than commercial airframes, engines, and related components. Although military R&D spending did not seek to catalyze commercial-aircraft innovation, technological spillovers from military to civilian applications were an important source of innovation in commercial aircraft. Innovation in commercial aircraft engines, for example, has benefited from military procurement and R&D spending since at least the 1920s and the Navy-financed development of the Pratt & Whitney Wasp piston engine. The development of the first U.S. jet engine was financed entirely by the U.S. military during World War II, based on British technology (see below). More recently, military-supported R&D on turbofan for the military C-5A transport led to the development of high-bypass engines that led to a new generation of commercial engines used on the Airbus A300, A310 and A320, as well as the Boeing 737-300, 747, 757, and 767 (see below).

Military-civilian technological spillovers of this type have been most important in aircraft propulsion technologies. But commercial airframe innovation also has benefited from military R&D and procurement spending. The most important source of airframe-related technological spillovers has been innovations in military transports, bombers, and tankers. As a result, the flow of such spillovers has fluctuated over time, reflecting changes in military priorities in aircraft-related R&D and procurement. Periods with substantial military R&D and procurement programs in these types of aircraft thus tend to be more important periods for military-civilian technological spillovers in airframe innovation. In the aftermath of World War II, the development of military jet-powered strategic bombers and tankers allowed civilian airframe producers to apply knowledge gained in military projects to commercial aircraft design, tooling, and production. The Boeing Company won military contracts for multi-engine, swept-wing strategic bombers (the B-47 and B-52) in the late 1940s, and gained significant design experience that influenced the firm's design of the commercial Boeing 707. The Boeing 707 airframe was based in part on the design of a military tanker, the KC-135, developed by Boeing to provide in-flight refueling for its strategic bombers. A major share of the development costs for the 707 was borne by the KC-135, as a comparison of the development costs for the 707 with those for the Douglas DC-8 reveals:

> Douglas lost $109 million in the two years 1959 and 1960, having written $298 million for development and production losses up to the end of 1960. Boeing did not suffer so badly. They wrote off $165 million on the 707 by then; some of the development cost may have been carried by the tanker program, which also provided a few of the tools on which the airliner was built. (Miller and Sawers, 1968, pp. 193-194).

Increased divergence between civilian and military aircraft technologies and mission requirements since the late 1960s appears to have reduced somewhat the amount and significance of military-civilian technological spillovers in both propulsion and airframe technologies. In some cases, technologies now flow from civilian to military applications. Whereas the Boeing 707 was a derivative of a military tanker design, the KC-10 military tanker, deployed during the 1980s, was a derivative of the DC-10 civilian airliner.[4] Similarly, as a National Academy of Engineering (NAE) study of the U.S. commercial aircraft industry noted in 1985, "Commercial engines gain service experience 10 to 15 times faster than military engines, even military transport engines…For example, some of the improvements in the DF6 turbofan engine (derived from the TF39 used in the C-5A military transport), developed during commercial service, are being incorporated in later versions of the TF39." (NAE, 1985, p. 101).

Military-civilian technological spillovers thus remain significant in the areas of propulsion, avionics, and flight control systems, but their economic importance has declined. Greater reliance by airframe and engine producers on industry-financed R&D and development programs means that these firms assume a greater share of the financial risk associated with the development of new generations of civilian commercial aircraft, a development that has contributed to exit by U.S. and European firms from independent commercial airframe development and production (see below for further discussion).

C. Industry-financed R&D

Industry-funded spending constituted a relatively small share of total U.S. aircraft-industry R&D spending throughout 1945-82 period, despite rapid growth in this source of investment. Industry-financed R&D investment never accounted for more than 23 percent of total R&D spending in aircraft throughout 1945-82, and during most of this period the industry-funded share rarely exceeded 20 percent. Industry-funded spending accounts for less than 10 percent of industrywide basic research spending—in other words, industry-financed basic research accounted for less than 1 percent of total aircraft-industry R&D spending during the period. Public sources, primarily the Air Force, Navy, and NASA (in the 1960s) supported the majority of basic research in the U.S. aircraft industry. Industry-financed spending has always accounted for a much larger share of nonmilitary aircraft R&D, however, growing from 42 percent in 1946 to nearly 64 percent by 1969.

V. The demand for innovation: The role of government regulation

[4] Boeing's design for the next-generation military tanker in the 2000s was based on its 767 commercial airframe.

The federal government played an important role in supporting innovation in the post-1945 U.S. commercial aircraft industry. But federal policy also supported the adoption by commercial airline firms of commercial-aircraft innovations through its policies governing transport of mail during the 1920s and early 1930s and during 1938-78, through the regulatory policies of the U.S Civil Aeronautics Board (CAB). Indeed, federal policy in commercial aircraft during much of the 20th century is unusual in affecting both the supply of new technologies and the adoption of innovations by the commercial air transport industry.

During the 1920s and early 1930s, the federal government used its control of mail transportation to support the introduction of innovations in civilian aircraft and the embryonic domestic airline industry (See Mowery and Rosenberg, 1982, for further discussion). The 1925 Kelly Air Mail Act opened U.S. domestic mail transportation to private contractors, and the generous terms of these government contracts led a number of firms, many of which were subsidiaries of commercial aircraft producers (see below), to enter mail transportation. The demand of airmail carriers for new aircraft led to the introduction of the Boeing 40, designed primarily for mail rather than passenger transport. The next major legislative initiative in domestic airmail transport, the McNary-Watres Act of 1930, was explicitly designed to promote innovation in civilian aircraft. The Act changed the terms of airmail contracts from a weight to a space basis—in other words, mail carriers were paid even if mail volumes on a particular route were low. In addition, the 1930 Act provided supplemental payments to carriers whose aircraft were equipped with multiple engines, navigational aids, and radio. The McNary-Watres Act contributed to a growth in domestic demand for new aircraft designs that ultimately led to the introduction of monocoque designs such as the Boeing 247 and the DC-3. Although its promotional effects were significant, controversies over the award of contracts resulted in yet another policy shift in the Air Mail Act of 1934, which shifted government airmail contracts to a strict "lowest-bidder" basis and mandated the divestiture by aircraft manufacturers of their airline subsidiaries. Nonetheless, federal government policies toward mail transportation supported the early growth of the civilian aircraft industry and domestic airlines,[5] and the 1925-29 period in particular was associated with a surge in civilian aircraft production (see below and Figure 9).
By the early 1930s, domestic airline transportation of passengers had become a significant industry, and Congressional dissatisfaction with air transport passenger safety regulation led to the establishment of the CAB in 1938. Through its power to issue operating certificates and its oversight of airline fares and route structures, the Board effectively controlled pricing, entry, and exit in the U.S. domestic air transportation industry from 1938 to 1978. The resulting regulatory environment restricted price competition among domestic carriers and spurred competition in service quality. One manifestation of service-quality competition was the rapid introduction of state-of-the-art aircraft. As Jordan's 1970 comparison of intrastate air transportation within California with interstate airline service pointed out, the interstate carriers, regulated by the CAB, consistently were faster to introduce such innovations as cabin pressurization and jet aircraft than were the unregulated California intrastate carriers who competed more aggressively on price:

> The trunk carriers were consistently the first to introduce each innovation. In fact, they introduced all but two of the over 40 aircraft types operated by all three carrier groups between 1946 and 1965. In addition, they adopted these innovations rapidly and extensively. The local carriers, on the other hand, were slow to introduce the two innovations and their rates of adoption were low. (Jordan, 1970, p. 53).

The drive to be first to introduce a new aircraft or other innovation led the major interstate airlines ("trunk carriers," in Jordan's terminology) to make early purchase commitments to U.S. aircraft producers as a means of obtaining the earliest possible delivery. The

[5] The number of domestic airlines grew from 13 in 1926 to 43 in 1930, before falling to 16 by 1938, and revenue passenger-miles grew from slightly more than 85,000 in 1930 (the first year for which U.S. data are available) to more than 316,000 by 1935 (U.S. Bureau of the Census, 1949, p. 224).

importance of an early position in the delivery queue also conferred considerable leverage upon commercial-aircraft producers in extracting advance orders from U.S. airlines, effectively defraying a portion of the cost of developing a new aircraft with advance payments from customers.

Service-quality competition caused airline operating costs to rise to the level of fares (see Douglas and Miller, 1976), and largely prevented domestic airlines from reaping supernormal profits from their protected position in the regulated market. Consumer welfare was also impaired by a lack of variety in service quality and price. In a 1977 study, the U.S. General Accounting Office concluded that a deregulated domestic air transportation system would reduce the annual costs borne by consumers by US$1.4 to US$1.8 billion (U.S. General Accounting Office, 1977). The CAB regulatory regime also affected the direction of innovation within the U.S. commercial aircraft industry, hindering the growth of the U.S. market for commuter aircraft. The modest demand for aircraft with 60 or fewer seats during this period reflected that the route structures developed by major U.S. airlines emphasized long-haul air travel, limiting any potential market for smaller "feeder" carriers. Indeed, Keeler (1972) argued that the major domestic airlines subsidized their short-haul routes from the profits earned in their protected interstate markets, further limiting the opportunities for short-haul carriers to enter. As a result, for much of the 1945-80 period, development of short-haul aircraft was undertaken largely by non-U.S. aircraft firms, including Fokker, Aerospatiale, Shorts Brothers, and deHavilland.

This market structure and its encouragement for the diffusion of new technologies was upended with the deregulation of domestic air transportation in 1978. Service-quality competition has largely vanished, and deregulation of entry has produced repeated waves of bankruptcies and restructuring among the interstate "legacy" airlines. The ability of commercial aircraft producers to extract substantial advance payments and thereby reduce somewhat the risks of new-product development has been diminished considerably. Along with the exit of several large, long-haul domestic airlines, the "post-CAB era" has witnessed the exit of several leading U.S. commercial airframe firms, notably Lockheed and McDonnell Douglas.

VI. "Breakthrough innovations" in the U.S. aircraft industry, 1900 – 75

This section examines the origins and effects of four "breakthrough innovations" in the U.S. aircraft industry. The first, the Wright brothers' original aircraft, is included in spite of the fact that it falls outside of the timeframe employed elsewhere in this paper for two reasons. First, the Wright brothers' innovation was the foundation of the U.S. and global aircraft industries, and therefore transformed the process of innovation in aircraft from one dominated by the independent research efforts of gifted amateurs (like the Wrights), academic researchers, and others to a process dominated by the efforts (often government-funded) of industry. Second, the Wright brothers' broad patent on their aircraft design limited entry by other U.S. firms into the production of aircraft and ultimately led to the formation of an industry-wide patent pool, the Manufacturers' Aircraft Association. Three other major innovations, ranging from the DC-3 airframe of the 1930s to the turbojet engine of the 1950s and the turbofan high-bypass engine of the 1970s, are also discussed. The choice of these three innovations reflects their significance for the development of the U.S. commercial aircraft industry.

A. The original "breakthrough innovation": The Wright brothers and their patent

The patent issued to the Wright brothers for their path breaking powered glider covered "all known means to laterally stabilize an airplane," and these broad claims were upheld by U.S. courts through litigation that spanned the 1908 – 14 period. The major protagonists in a welter of patent-infringement suits and countersuits during this period were the Wright Corporation, incorporated in 1909 and based in Dayton, Ohio, and the Curtiss Aeroplane Company, originally located in Hammondsport, NY, an assignee of other aircraft-related patents. Glenn Curtiss, a motorcycle mechanic, had developed a series of lightweight internal-combustion engines and explored applications of his internal-combustion engines to powered flight with a research group sponsored by Alexander Graham Bell, the inventor of the telephone.[6] The airframe designs developed by the Curtiss firm to exploit their innovative engines attempted to "invent around" the broad Wright patent by relying on a new technology, wing flaps, for control of the aircraft. Even this alternative technical solution, however, was ruled as infringing on the Wright patent in a 1914 appellate decision. Ironically, by the time this decision was rendered, the Wright Company had largely abandoned the brothers' original "wing-warping" approach in favor of one that closely resembled Curtiss's wing flaps. Nonetheless, with the backing of the U.S. courts, the Wright firm sought royalties of $1,000 on any aircraft manufactured in the United States. The patents granted to the Wrights in Europe were viewed more skeptically by German and French courts, which may have contributed to higher levels of entry into their nations' aircraft industries by French and German firms in the years immediately prior to World War I.[7]

The tangled patent landscape that characterized the U.S. aircraft industry on the eve of World War I, as well as minimal support from the U.S. military for aircraft development and procurement, was associated with slow growth in the domestic aircraft industry. Estimates of the number of active aircraft producers for this period are less than reliable; Rae (1968, p. 1) cites a total population of 16 U.S. producers of aircraft in 1914, and the 1913 edition of *Jane's All the World's Aircraft* (Jane, 1913) lists 13 firms. It is very plausible that the outbreak of war in Europe in 1914 triggered additional firms to enter, raising the total number of U.S. firms from 13 in 1913 to 16 in 1914. Nonetheless, the industry's output of aircraft was modest, far smaller than that of the leading European nations (belligerents in World War I). *Total* U.S. aircraft output in 1914 (commercial, private, and military) amounted to 49 units in 1914.

Although U.S. entry into World War I eventually triggered a significant expansion in U.S. aircraft production, the expanded U.S. output consisted largely of European designs—Curtiss produced seaplanes and training aircraft, but no U.S.-designed fighter aircraft saw service during wartime.[8] As combat in Europe during 1914 – 16 revealed the potential military applications of aircraft, U.S. government officials, notably the Secretaries of War and the Navy, became concerned over the patent situation and the apparent standoff between the Wright Company and Curtiss. Their concerns were supported by Congressional opposition to the sweeping control over firm entry sought by Wright, and legislation was introduced to invalidate the original Wright patent. This intense pressure on the Wright firm in particular appears to have contributed to the resolution of the patent dispute between Wright and Curtiss, resulting in the formation of the Manufacturers' Aircraft Association (the

[6] The Bell group benefited from the Wrights' decision in 1908 to share technical data from their experiments, although the Wright firm sued Curtiss and his backers as soon as an aircraft that drew on these data was sold to the Aeronautical Society of New York (Goddard, 2003, p. 184).

[7] "The patent litigation spread to Europe in 1910, when the Wright licensees, the Compagnie Gelerale de Navigation Aerienne (CGNA), brought suit against six rival aircraft manufacturers (Bleriot, Farman, Esnault-Pelterie, Clement-Bayard, Antoinette, and Santos-Dumont) for infringing on the Wright's French patents. The following year, a consortium of five German aircraft builders brought suit against the incorporators of the German Wright Company in an effort to overturn the Wright patents in that nation.

"The Wrights found that the patent suits were an effective means of dealing with independent [U.S.] operators like Paulhan and Graham-White. The cases involving the Curtiss Company and European firms were more difficult, expensive, and time consuming, however, and seldom produced a clear-cut resolution. The courts invalidated the Wright's [sic] German patents, arguing that prior disclosure, the publication of information on the basic elements of the Wright airplane before the approval of their patent, had compromised their claims. The French suit, complicated by a very different legal system and the absence of spirited prosecution by the CGNA, was still not fully resolved when the Wright's [sic] French patents expired in 1917." (Crouch, 2000, p. 288).

[8] "Although Americans pioneered the development of heavier-than-air flying machines, European countries soon wrested technology leadership away from the United States. Indeed, U.S. aircraft manufacturers soon fell so far behind the Europeans that they did not design and develop any fighters used in combat during World War I. U.S. fighter squadrons that deployed to Europe flew foreign-designed fighters, such as the famous French SPAD S.XIII and the Nieuport 17." (Lorell and Levaux, 1998, pp. 16-18).

MAA) in 1917. For additional discussion of the MAA and the overall role of patents in the U.S. aircraft industry, see below.
U.S. entry into World War I caused a significant expansion in the production of European-designed military airframes and the U.S. Liberty engine by U.S. firms, as output reached 14,000 aircraft in 1918 (Rae, 1968 p. 2). The surge in military demand was associated with a surge in entry by new firms—5 of the 9 founding members of the Manufacturers' Aircraft Association were established between 1914 and 1917. By the end of 1918, however, production contracts amounting to more than $100 million had been cancelled and the U.S. industry had shrunk significantly.

During 1920-34, military and commercial aircraft design and production activities became more distinguishable from one another. U.S. military aircraft production declined from 14,000 in 1918 to 263 in 1922 (Holley, 1964), but slowly revived thereafter, as the U.S. military announced its intention to maintain a fleet of 26,000 aircraft by 1931. Military support for aircraft engine development during this period led to the formation in 1925 of the Pratt & Whitney engine firm, producer of the Wasp engine for naval aircraft. The overall economic boom of the 1920s, combined with such milestones as the Lindbergh transAtlantic flight of 1927 and the Air Mail Act of 1925, produced rapid growth in the U.S. aircraft and airline industries. The data in Table 2, which are summarized in Figure 8, depict the surge in U.S. civil aircraft production during the 1920s—the number of units produced doubled between 1926 and 1927, and more than doubled between 1927 and 1928, before production was severely reduced with the onset of the Great Depression in 1929.

Increased production during the 1920s was associated with increased private investment in the U.S. aircraft industry. Total investment in the industry grew from $15 million in 1926 to more than $250 million by 1929, before a sharp decline in the 1930s. Although a number of firms entered the industry during the 1920s, including Douglas Aircraft, Lockheed, Ryan Aeronautical, and Grumman, the revival of the aircraft industry during this period was also characterized by a series of mergers that produced several large firms that combined airframe and engine production with air transportation services. United Aircraft, founded in 1929, included Boeing Aircraft, Boeing Air Transportation, Pratt & Whitney, Chance Vought Aircraft, the Hamilton Standard Propeller Corporation, and Stearman Aircraft. Former litigation opponents Curtiss Aeroplane and Wright Aeronautical merged in 1929 to form Curtiss-Wright. The Aviation Corporation (AVCO) was established in 1929, and owned Fairchild Aircraft and several small airlines. North American Aviation was founded in 1928 as a holding company that at various times subsequently owned (and subsequently divested) portions of Douglas Aircraft, Curtiss-Wright, and Transcontinental Air Transport and Western Express (later combined to form TWA). The Air Mail Act of 1935 mandated the divestiture of their commercial airline subsidiaries by these large aircraft producers, and United and Boeing Aircraft also were separated during the 1930s.

B. The "breakthrough innovation" of the 1930s: The DC-3

The data on direct operating costs per seat-mile in Figure 7 highlight the remarkable increase in efficiency represented by the Douglas DC-3, introduced in 1936. Miller and Sawers (1968) estimate that the operating costs of the DC-3 were nearly 50 percent lower than those of the Ford Trimotor, introduced a decade earlier. Indeed, the efficiency advance associated with the introduction of the DC-3 was equaled only by the wide-body transports that entered service 35 years later. The aircraft's low operating costs reflected its use of advances in materials, aviation fuel, engine technologies, and design. The DC-3's engines represented a significant advance in power without a corresponding increase in weight, according to Miller and Sawers (1968): "The most striking feature of the progress of the decade of the 1930s was that more power was obtained from engines of the same size [weight]." The low weight-to-power ratio of the DC-3 engines enabled the aircraft to transport a larger number of passengers than previously had been feasible without severe fuel-consumption penalties. The improvements in engine design underpinning these advances drew on R&D supported by the federal government (NACA and the U.S. military) and relied as well on improved aviation fuels, especially the addition of tetraethyl lead to aviation fuels, that resulted from R&D supported by DuPont, General Motors, NACA, and the National Bureau of Standards.

The DC-3's airframe was not a radical advance, instead representing an improved all-metal, monocoque low-wing design. The monocoque design concept was pioneered by German aeronautical engineers Rohrbach and Wagner in the 1920s and incorporated into the design of several single-engine aircraft produced by Boeing (the Monomail) and Lockheed (the Vega). The 1931 crash of a Fokker trimotor that killed the famous Notre Dame football coach Knute Rockne led the federal government to ban the Fokker from passenger transportation. This regulatory step created an urgent need for a low-cost air transport that motivated Boeing to develop the B-247, an all-metal low-wing design, and led to Douglas Aircraft's DC-2 and DC-3.

The DC-3 airframe incorporated a number of important research advances from NACA-supported R&D, including the cowling on the aircraft's engines, the placement of the engines on the leading edge of the wing, and retractable landing gear. Wing flaps and variable-pitch propeller technologies improved the handling of the aircraft in the landing and takeoff stages of flight. The basic wing design of the DC-3, which proved to be enormously sturdy and enabled the aircraft to enjoy a lengthy service career in both military and civilian applications, also drew extensively on NACA R&D, as Phillips (1971) noted:

> …the wings of the DC-3, as well as those of the other planes of its generation, owe their origin to NACA and other non-commercial or non-United States research. In particular, the DC-1 had a NACA 2215 wing section at the root—with fillets into the fuselage which were the results of NACA research—and a NACA 2209 section at the tip. (p. 117)

The strength of the airframe and wing design benefited as well from new materials, most notably a new duralumin alloy developed by Alcoa. The design and integration of these many advances in component technologies and materials, ranging from metals to fuels, was little short of brilliant. But it was the synthesis of these technical advances, many of which drew on sources of R&D funded or performed outside of Douglas Aircraft, which enabled the quantum advance in efficiency represented by the DC-3.

Because its operating costs were so much lower than contemporary or previous passenger aircraft, the DC-3 contributed to the growth of commercial air transportation in the United States during the 1930s and 1940s. Domestic revenue miles flown in the United States, for example, nearly doubled between 1936, the year that the DC-3 entered commercial service, and 1941, the last year of peacetime, increasing from slightly more than 64 million revenue miles in 1936 to more than 134 million in 1941 and nearly 370 million in 1950 (U.S. Bureau of the Census, 1949, p. 224; U.S. Bureau of the Census, 1975, p. 769).[9] Sales of the DC-3 dominated the market for commercial airliners after its introduction—during the 1936-41 period, the aircraft accounted for more than 86% of deliveries to U.S. domestic trunk airlines (Phillips, 1971, p. 94).

Finally, it is important to note that no single patent covered the DC-3. Although many (but by no means all) of the individual advances in materials, propulsion and design that were combined in the final design were patented, the "breakthrough" innovation of the DC-3 itself was not covered by a patent, in contrast to the Wright Brothers' original aircraft.

[9] International revenue miles grew from slightly less than 7 million in 1936 to nearly 95 million by 1950 (U.S. Bureau of the Census, 1975, p. 770).

C. The “breakthrough innovation” of the 1950s: the jet-powered commercial airliner

The next “breakthrough innovation” in air transportation was the jet-powered commercial airliner, which entered service in the 1950s. Like the DC-3, this “breakthrough” required technical advances on many fronts, as well as increased scientific knowledge of aerodynamics, a field in which U.S. researchers lagged behind European (particularly German) scientists and engineers until the 1940s. The weaknesses in U.S. aerodynamics research, according to Constant (1980) and others (including Young, 1997, and Holley, 1988) essentially prevented U.S. industrial, military and government researchers from recognizing the military and commercial potential of jet-powered flight until the 1940s, at least a decade after British and German researchers began working on the challenge. Their unfamiliarity with advanced aerodynamics meant that U.S. designers failed to appreciate the feasibility of swept-wing airframe designs of the type that yielded significant performance gains when equipped with jet engines, although most were aware of the technical feasibility of the turbojet engine.

Experimental models of gas-turbine propulsion technologies were demonstrated in France in 1906 and in the United States in 1907, and the first patent for a turbine-based aircraft propulsion technology was issued in France in 1921.[10] Reflecting the widespread diffusion of the knowledge base related to turbine-based propulsion, inventive activity related to the turbojet engine began almost simultaneously in Great Britain and Germany under the leadership of three individuals: Frank Whittle of Great Britain, who worked independently for nearly a decade after 1929 before receiving significant financial support from the UK government; Otto von Ohain of Germany, who worked with the Heinkel Aircraft Company of Germany through the 1930s; and Herbert Wagner of the Junkers Aircraft Company, whose development work was supported by the German Air Ministry during the 1930s as part of German rearmament. The first successful jet engines were deployed on German military fighter aircraft that incorporated significant airframe design advances, including stronger wing designs and swept wings. The development of these aircraft in the late 1930s and early 1940s was funded almost entirely by the military services of Britain and Germany.

Intelligence reports on the German jet-engine development program reached U.S. military authorities in late 1940 and led NACA to appoint a “Special Committee on Jet Propulsion” in 1941. An additional impetus to U.S. development activities in this area was U.S. Army Air Force General Arnold’s presence in May 1941 at a successful test flight of a British jet-powered fighter aircraft. Arnold negotiated the transfer of the basic specifications and blueprints for the British jet engine, developed largely by Whittle for the U.K. Air Ministry, to the U.S. War Department, and funded a development contract with General Electric for the development of a U.S. prototype jet engine based on the Whittle design. The willingness of the British Air Ministry to transfer this military technology to the U.S. government on a royalty-free basis underscores both the perilous position of Britain in 1941 and the lack of patent-related impediments to such a transfer.[11]

Much of the essential research underpinning both the design of the high-speed turbines and compressors needed for the turbojet engine and the swept wings that were necessary to exploit the operating efficiencies of the jet engine rested on scientific advances from

[10] Illustrating the complexity of the jet engine “invention,” Constant (1980, p. 179) notes that the 1921 patent application of Charles Guillame, “…in addition to showing the expected compressor, combustion chamber, and turbine, also show, protruding from the front of the engine, a very large manual starting crank…Guillame’s concept, in short, although of the same configuration as a turbojet, could not have been farther from the valid scientific assumptions that made the turbojet a practicable possibility. To say that he ‘invented’ the turbojet in any meaningful sense is absurd.”

[11] According to Whittle (1979), British development of its jet engine technology had been hampered by German bombing raids, and the willingness of British military leaders to have U.S. firms become involved in jet engine development was based in part on the recognition that development sites in the United States were far less susceptible to air raids.

Germany. Academic researchers at the Universities of Gottingen and Aachen, including Theodor von Karman and Ludwig Prandtl, pioneered in the study of aerodynamics. The Gottingen researchers were funded by industry and government through the Gottingen Association of Applied Physics and Mathematics, established in the late 19th century. And during the 1920s, the contributions of these German researchers were widely disseminated through scientific publications and summaries in English technical journals.[12] International scientific conferences, most notably the Volta High Speed Conference that met in Rome in the autumn of 1935, served as venues to demonstrate German leadership in research[13] and to disseminate their scientific results more broadly.

Another important development in the recognition within the U.S. scientific and engineering community of the importance of theoretical research on aerodynamics was the decision by von Karman in 1929 to accept the directorship of the Guggenheim Aeronautical Laboratory at the California Institute of Technology. The Laboratory was financed generously by Harry Guggenheim, heir to a large fortune based on U.S. mining and industrial activities.[14] Guggenheim funded aeronautics research laboratories at 6 other U.S. universities (New York University, MIT, Stanford, the University of Michigan, the Georgia Institute of Technology, and the University of Washington), but the CalTech laboratory proved to be the most influential, in no small part because of von Karman's brilliance and charisma. For his part, the decision by von Karman, born to Jewish parents in Hungary, to emigrate from a prestigious position at Gottingen to the scientific backwater of the West Coast of the United States was fueled in part by a growing awareness of the nationalistic and anti-Semitic views of the National Socialist party, which came to power in 1933. Having served as a visiting member of the CalTech faculty from 1929-33, von Karman resigned his German professorship in 1934.

As the above paragraphs suggest, the conventional channels of scientific communication, such as publishing and scientific conferences, had disseminated much of the fundamental knowledge underpinning advanced aerodynamics and turbojet design to U.S. and other nations' scientists. But access to codified scientific knowledge does not always support the ability to exploit such knowledge for innovation. Indeed, U.S. engineers had examined the possibilities for turbojet applications in aircraft as early as the 1920s at the U.S. National Bureau of Standards. In 1924, the lead researcher on the project, Edgar Buckingham, stated that the jet engine was technically feasible, but jet-powered flight was impractical

[12] "The British semitechnical journal *Engineering*, which had shown interest in German research by publishing as early as 1911 translated extracts from Prandtl's contributions to *Zeitschrift fur Flugtechnik*, examined at length and with diagrams Prandtl's new aerodynamics laboratory, which had been completed during the war. The warrant for this review was the appearance in 1921 of the first volume of Prandtl's *Results of the Aerodynamics Research Institute at Gottingen, and Engineering* summarized the introductory sections of that volume. Two other British journals, *Aeronautical Engineering*, the technical supplement to *The Aeroplane*, and *The Journal of the Royal Aeronautical Society*, a vehicle of advocacy but one held in high regard, undertook reviews based on the same work. The latter, appearing in 1924, emphasize the 'able direction' of Prandtl and noted that Gottingen was 'the chief centre of aeronautical research in Germany.' These reports were widely read by aviation enthusiasts in American as well." (Hanle, 1982, p. 85).

[13] Based on his survey of the papers presented at the Rome conference, Constant (1980) concluded that "…both qualitative and limited quantitative evidence suggest that German or German-educated scientists led in theoretical investigations of high-speed and turbocompressor phenomena, that Btitish scientists lagged only slightly behind as late as 1935, and that scientists in the United States, Italy, and France lagged far behind. American scientists did, however, produce unmatched empirical design data for normal subsonic aircraft and for piston engine-propellor propulsion systems." (p. 156). Adolf Busemann, a faculty researcher at Gottingen and after 1947, a member of the US Air Force's scientific staff, presented the first public paper on swept-wing technology at the Volta conference.

[14] Guggenheim's generous support of the CalTech laboratory was solicited by Robert Millikan, a Nobel Prize-winning physicist who became the Institute's president in 1921. Millikan's interest in developing CalTech research in aeronautics was motivated in part by his interest in supporting the aircraft industry that by the mid-1920s was a growing presence in Southern California, and the Guggenheim Laboratory worked closely with Douglas Aircraft in the design of what became the DC-3 (See Hallion, 1977).

because of high operating expenses at the projected cruise speeds of roughly 250 mph.[15] Exploiting the potential for turbojet-powered military or civilian aircraft required radically new designs for airframes that could achieve higher cruise speeds.

The failure of U.S. scientists and engineers to apply emerging advances in aerodynamic theory to airframe design reflected the lack of funding for basic research in these fields. Although NACA's contributions to the DC-3 and other aircraft of that generation were considerable, historians argue that NACA largely supported incremental, technical research on existing propulsion and airframe technologies through the 1920s and 1930s. The U.S. military services also failed to support basic research, and relied primarily on NACA for their technical understanding of the possibilities for technical advances in aviation.[16]

By the end of World War II, Great Britain had fielded a jet-powered fighter aircraft, while the United States had developed a prototype (the P-59) that was eventually to see use as a training aircraft. Nearly a decade passed before the first jet-powered commercial aircraft, the deHavilland Comet, appeared in 1952. One obstacle to widespread applications of turbojets in commercial aircraft was the high level of performance of piston-powered aircraft then in extensive use, ranging from the Boeing 307 to the DC-4. More powerful turbojet engines were needed, as well as new airframe designs that could accommodate multiple jet engines and thereby carry larger passenger payloads in order to support the widespread adoption of jet-powered commercial aircraft. The development of such engines and airframes benefited from military programs focused on the development of jet-powered strategic bombers for the U.S. Air Force.

The design of the airframes for these military bombers required a deeper understanding of aerodynamic theory than the U.S. aircraft industry, government, or academic researchers were able to muster until the late 1940s, when the disclosure of German technical information from wartime fighter aircraft development programs and the emigration of German engineers led to significant advances in U.S. design capabilities.[17] According to John Steiner, one of the members of the design team for the Boeing B-47 and B-52, the first long-range jet-powered bombers purchased by the U.S. Air Force, the recognition by Boeing engineers of the potential performance benefits of swept wings on these aircraft resulted from the travel by the firm's chief aerodynamics engineer to the Luftwaffe research facilities in Braunschweig on the date of the German surrender in May of 1945.[18]

[15] Miller and Sawers (1968, p. 153) note that the performance advantages of jet-powered transports are significant only at cruise speeds above 450 mph.

[16] Young (2007, p. 15) argues that "Industry depended on the Air Corps for direction in terms of requirements, and the Air Corps, in turn, depended on the NACA for fundamental research. Because the piston engine appeared to be such a given, the military never called on the NACA to investigate radical new forms of propulsion and the NACA, in turn, virtually abandoned the field, leaving it up to industry and the military. However, industry did not have the incentive to take on the job and the military did not have the expertise to look in new directions or even to direct either industry or the NACA to do so." Constant (1980) makes a similar point.

[17] Neufeld (2012, p. 53) estimates that as many as 700 German scientists with experience in wartime R&D programs were brought to the United States, almost all with the "sponsorship" of the U.S. military services, through 1953. Roughly 2/3 of these individuals were aerospace scientists and engineers. By the end of the 1950s, according to Neufeld, more than 1300 former German scientists and engineers had entered the United States, although a growing share of this outflow from Germany represented voluntary emigrants. German scientists and engineers with wartime R&D experience also emigrated (voluntarily and otherwise) to the Soviet Union, Great Britain, Canada, Australia, and the Netherlands in the immediate aftermath of World War II, in most cases with the sponsorship of these nations' governments.

[18] "…as World War II drew to a close in Europe, the U.S. sent combined military and civilian technical groups to ascertain the latest level of German technology. Mr. Schairer [chief aerodynamics engineer at Boeing] joined the Dr. von Karman team and arrived at Reichsmarshal Goering's Aeronautical Research institute at Braunschweig the morning Germany surrendered…The Boeing bomber team [designing what became the B-47] was redirected by George's letter sent May 10, 1945, which told us to investigate sweepback, which we did, although not without the usual resistance from within the organization." (1979, p. 142). Ciesla and Krag (2010, p. 654) note that

The deHavilland Comet benefited from Britain's leadership in jet engines while arguably suffering from the deHavilland firm's failure to master the demands of airframe design for jet-powered commercial aircraft. Development of the Comet began in 1946, and the aircraft was originally intended to provide rapid transport of mail. DeHavilland had limited experience in commercial aircraft design, having produced only two commercial airframe designs before World War II, and the firm's experience with jet-powered military aircraft was also limited, consisting of its production of the single-engine Vampire fighter aircraft.

The Comet was introduced into commercial service in 1952, using deHavilland's Ghost jet engines and a relatively small airframe with minimally swept wings and a capacity of 36 passengers. Although its modest passenger capacity resulted in operating costs that were higher than those of the contemporary piston-powered DC-6, its speed meant that airlines could charge a premium for passenger service. The Comet unfortunately experienced a series of catastrophic crashes caused by the failure of its airframe, a failure that resulted from metal fatigue associated with the effects of frequent takeoffs and landings that stressed

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Schairer requested in his May 1945 letter that other U.S. aircraft firms be informed of the German advances with swept-wing designs. According to Steiner (1979, p. 146), Dr. Waldemar Voigt, another German aeronautics engineer who had been involved in wartime German research and emigrated to the United States after the end of the war, served as to the U.S. Air Force staff at Wright Field and provided additional encouragement to the Boeing B-47 design team to rely on swept-wing designs.

A more detailed account of the importance of the U.S. technical teams' 1945 fieldwork in Germany that highlights the diversity of international sources of scientific expertise for post-1945 U.S. military jets is found in Bilstein (2000, pp. 215-216): "The American chapter of the swept wing story originated with Michael Gluhareff, a graduate of the Imperial Military Engineering College in Russia during World War II. He fled the Russian revolution and gained aeronautical engineering experience in Scandinavia…By 1935, he was chief of design for Sikorsky Aircraft and eventually became a major figure in designing the first practical helicopter…

"In a memo to Sikorsky in 1941, he [Gluhareff] described a possible pursuit-interceptor having a delta-shaped wing…Wartime exigencies derailed Gluhareff's 'Dart' configuration until 1944, when a balsa model of the Dart, along with some data, wound up on the desk of Robert T. Jones, a Langley [NACA's Langley facility] aerodynamicist. Studying Gluhareff's model, Jones soon realized that the lift and drag figures for the Dart were based on outmoded calculations for wings of high-aspect ratio. Using more recent theory for low-aspect shapes, backed by some theoretical work published earlier by Max Munk [a Gottingen-educated German aerodynamicist who had worked at NACA during 1920-29], Jones suddenly had a breakthrough. He made his initial reports to NACA directors in early March, 1945. Within weeks, advancing American armies captured German scientists and test data that corroborated Jones' assumptions. Utilization of these collective legacies, as well as wartime studies on supersonic wind tunnels by Antonio Ferri, of Italy, all leavened successful postwar progress in high-speed research and aviation technology."

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the fuselage through repeated repressurization. The Comet I was withdrawn from service in 1954, and deHavilland was unable to re-enter the commercial aircraft market until 1958. This long absence proved disastrous for the firm's prospects in jet-powered aircraft, especially since the Boeing 707 and DC-8, both of which used more powerful engines to power much larger airframes, entered service respectively in 1958 and 1959, and proved to be more durable and efficient. DeHavilland's difficulties with its pioneering Comet airliner highlight the pervasiveness of uncertainty about the performance of new aircraft that incorporated novel airframe and engine designs. Although theoretical knowledge of aerodynamics was indispensable to development of the jet-powered commercial airliner, such knowledge did not yield a strong foundation for predicting performance or safety.

Like the development of the DC-3, the introduction of commercial jet airliners illustrates the complexity of commercial aircraft technologies. Innovations across a wide range of technologies, ranging from materials to engines to fuel, were necessary for the commercial jet airliner to become a reality. In addition, of course aircraft designers needed a theoretical foundation of knowledge to guide the design of airframes that could exploit the new possibilities created by turbojets.[19] As was noted repeatedly above, "knowledge" of the feasibility and possibilities of turbojets was widespread at least three decades before the first flight of a commercial jet. Indeed, the very ubiquity of this knowledge helps explain why the jet engine was "invented" at nearly the same time in two nations by three different teams of engineers.

Both Whittle and von Ohain patented their early turbojet prototypes. According to Whittle, "…a Provisional Patent Application was fuly filed on January 16th, 1930, and a Patent was granted about 18 months later…Because of [UK Air] Ministry disinterest, it was not placed on the secret list, and so, in mid-1932 it was published and became available worldwide." (Whittle, 1979, p. 4). Von Ohain received a patent on his jet-engine design in 1935, but asserted in a 1979 account (von Ohain, 1979, p. 29) that he was completely unaware of the Whittle patent, which was not renewed in 1935 because of Whittle's failure to enlist significant funding for development of the technology.[20]

In the case of the jet engine (unlike the original Wright aircraft design), it is difficult to identify any single "blocking patent," or even a group of key patents that obstructed entry. Much of the basic scientific knowledge underpinning both the turbojet engine itself and the design of innovative airframes to exploit the potential of this new propulsion source had been disseminated throughout the global scientific community by 1940, although it is apparent that U.S. aircraft designers employed in industry had little acquaintance with these advances. The prominent role of government funding of jet-powered aircraft during and after World War II also meant that much if not all codifiable firm-specific knowledge was shared among erstwhile competitors, further weakening a case for the use of patents to exclude others. It is of course possible that patents in the field of jet engines served to disseminate technical details of this innovation, but there is little discussion of patents in the lengthy process of innovation surrounding this technology, and no evidence of any role for patents in communicating technical details.

D. The "breakthrough innovation" of the 1970s: High-bypass turbofan engines

[19] As Constant (1980, p. 129) points out, "If a fully developed turbojet had been delivered to the Wright brothers or to any one of the belligerent air forces during the First World War, and if they had had the electrical system and the fuel system to get the engine into operation, which they did not, the engine would have promptly jerked apart any aircraft in which it might have been installed."

[20] Like other leading German researchers in aeronautics and propulsion, von Ohain was brought to the United States by the U.S. Air Force in 1947 as a researcher and in 1975 was appointed Chief Scientist in the Air Force Propulsion Laboratory at Wright-Patterson Field.

As Figure 7 indicates, the last major increase in performance efficiency during the 1908-75 period, measured in seat-mile operating costs or AS*Vc, occurred in the early 1970s with the introduction of the wide body commercial transports (the Boeing 747, the McDonnell Douglas DC-10, and the Lockheed L-1011). The performance improvements associated with these airliners flowed largely from their significant increases in passenger capacity, as well as the unprecedented operating efficiency of their turbofan engines, which produced much greater thrust than the previous generation of turbojets. The "high-bypass" turbofan engines on all of these aircraft relied on advances in materials and design that enabled a higher fraction of the total airflow to "bypass" the central core of the engine, thereby enabling the achievement of higher thrust and greater operating efficiency. The airframes on all of the widebody aircraft introduced during 1970-75 represented important advances in design that relied on improved materials such as aluminum-lithium alloys. Nevertheless, these airframes were largely incremental advances—the critical technical advance that enabled the introduction of these larger aircraft was the high-bypass engine, which originated in U.S. military development programs of the 1960s.

The U.S. Air Force sponsored a competition during the early 1960s between Lockheed and Boeing to develop a new military transport with greatly increased capacity and improved operating efficiency. The Air Force contract for the C-5A transport that resulted from this competition was awarded to Lockheed in 1965. The C-5A utilized a high-bypass engine developed by General Electric (with a bypass ratio of 8:1, meaning that slightly more than 10% of the air passing through the turbofan engine went through the central compressor & combustion unit), the winner of a parallel Air Force engine-development competition that pitted GE against Pratt & Whitney. Pratt & Whitney's failure to win the C-5A engine contract led the firm to approach Boeing with a proposal for an airliner of unprecedented passenger capacity, which became the Boeing 747, introduced into commercial service in 1970.

The Boeing 747 was developed in large part at the behest of Pan American Airways, which sought an aircraft capable of lengthy international flights with larger passenger capacity than the Boeing 707. Their initial discussions with Lockheed about the concept having been unsuccessful, Pan American placed an order with Boeing for 25 of the new aircraft in 1966 and insisted on a very tight schedule for its introduction. Although the airframe design for the 747 relied on proven principles and drew on Boeing's substantial experience with commercial jet airliners, the project faced significant technical challenges associated with the fact that a new airframe design was being developed for engines with no military or commercial operating history. Indeed, the problems that Pratt & Whitney experienced in developing its new JT8 high-bypass engines introduced significant delays into a project already operating on a schedule less than two-thirds as lengthy as previous Boeing commercial airliner projects (See Sutter, 2006, for details). Pratt & Whitney's difficulties with the development of its high-bypass engines underscore the uncertainties associated with the integration of the complex systems that is required for innovation in commercial aircraft. Similar technical difficulties with the development of new high-bypass engines by Rolls-Royce created major delays in the development of the Lockheed L-1011 and forced both Lockheed and Rolls-Royce to seek government-funded financial bailouts.

Although the Boeing 747 development project proved to be financially demanding and risky for the firm, the 747 has enjoyed considerable commercial success and modified versions remain in production nearly 45 years after the aircraft's introduction. The L-1011 and DC-10 did not enjoy commercial success, reflecting the fact that these aircraft competed with one another and their shorter range made them less useful for international flights. The high-bypass engine, however, is used on virtually all commercial jetliners that seat 100 or more passengers, with designs produced by Pratt & Whitney, General Electric, and Rolls Royce.

VII. The role of patents in the 20th-century U.S. aircraft industry

A. Aircraft technology and patents

The large literature on the history of innovation in the aircraft industry contains few discussions of the role of patenting by inventors other than the Wright brothers or Glenn Curtiss. Most historical accounts of the industry dismiss patents as an important factor in either inventive behavior or the competitive strategies of aircraft firms.[21] There appear to be several reasons for this characterization of patents as relatively unimportant in the aircraft industry, including the nature of aircraft technology, the role of the Manufacturers' Aircraft Association (MAA) within the U.S. industry, and the important role of governments as sources of R&D and procurement funding in the U.S. and other industrial nations' aircraft industries throughout the 20th century, and especially after 1945.

Meyer's work (Meyer, 2013) on inventive activity in aircraft during the "pre-industrial" phase of technological development (i.e., before the Wright brothers demonstrated the feasibility of heavier-than-air powered flight during 1903-08 and established their aircraft company) argues that this "pre-industrial" phase of inventive activity in aircraft resembled the "open-source" model of innovation in some areas of the contemporary software industry. Individuals from academia, government, and elsewhere experimented with new approaches to flight, largely as independent researchers, while sharing data and technical details with one another. Indeed, the Wright brothers were providing technical data to future competitors as late as 1908. But the recognition by leading inventors of the possibilities for profitable sales of aircraft and engines (largely to governments before 1920) led to the establishment of competing firms and a shift to treating firm-level knowledge as proprietary.

Even after the development of something that could be referred to as an "aircraft industry," populated by private firms seeking profit through innovation, a substantial international cadre of scientific researchers remained active in government and academic research facilities, and shared their knowledge through publication and public lectures. The concept of the swept wing, for example, was not a technical secret held closely by a single firm or government, but was disclosed by Busemann at the international Volta High Speed Conference in 1935. Similarly, as Eckert (2005) points out, Ludwig Prandtl and colleagues from Gottingen University, who were leaders in aerodynamics research and contributors to Germany's World War I military aircraft programs, participated in the International Congresses of Applied Mechanics, "…regular meeting places for the international elite of applied mathematicians and theory-minded mechanical engineers." (p. 126) that were held in 1924, 1916, and 1930. As I noted earlier, NACA facilitated the inward flow of scientific aerodynamics knowledge to the United States during the 1920s through its work with Ludwig Prandtl and the hiring of Max Munk in 1922. The growth of the aircraft industry during and after World War I thus did not end the exchange of technical and scientific data, models, and theories among aircraft scientists and engineers, although the content of these flows may have changed somewhat.

In the case of both the Wright brothers and Glenn Curtiss, patents played an important role as weapons in competitive strategy during the decade between roughly 1908 and 1914. But there are few if any subsequent examples of broad patents on major advances in aircraft technology. There is little evidence of critical "blocking" patents in the breakthrough innovations of the 1930s, the 1950s or the 1970s that were discussed above. In part, the relative unimportance of patents reflects the nature of aircraft technology. As I have noted

[21] The authoritative account of the development of aircraft technology by Miller and Sawers (1968, p. 255) concludes that "…in the aircraft industry the utility of patents seems to be less than it is in many other industries. It is often difficult to patent an important technical improvement in the design of an airplane. There was little that was patentable about the improvements in the aerodynamic efficiency of airplanes, or about the recent growth of knowledge on supersonic flow, so the aircraft manufacturer places less trust in patents as a protection for his technical achievements than do manufacturers in many other industries. He relies mostly on secrecy until a new airplane appears, then on the time-lag before a competitor is able to produce an airplane incorporating the idea." Roland (2000) and Chapin (1971) also contain skeptical accounts of the importance of patents in the aircraft industry.

elsewhere in this paper, aircraft are complex products that require the integration of thousands of components to perform safely and efficiently. Indeed, this complexity contributes to the uncertainty about the performance of new designs that typified the aircraft industry through much of the 20th century (the Comet is but one example). This complexity means that patents on individual component technologies rarely can effectively exclude competitors or preserve a firm's market position—alternative components or architectures typically enable other firms to "invent around" patents. The ability to predict the interaction among these components and to integrate them effectively within a production process is a critical source of firm-specific knowhow that rarely is patented and generally resists codification. Complexity and uncertainty also contribute to the importance of incremental innovation in the aircraft industry, in which individually modest but cumulatively significant innovations are frequent, rarely patented, and often based on experience in either the production or operation of an airframe design.

B. The U.S. Manufacturers' Aircraft Association

In addition to the nature of aircraft technology, the relative unimportance of patents within the U.S. aircraft industry reflected the influence on industry practices of the patent pool that operated for nearly 60 years as the Manufacturers' Aircraft Association. Although the MAA was established largely to overcome the restrictive effects of the broad patents that were believed by contemporary observers to be obstructing the development of the U.S. aircraft industry, the creation of the MAA assuredly weakened the role of patents within the industry. The agreement establishing the MAA resolved the patent dispute between the Wright and Curtiss firms by granting financial concessions to each, and required that all member firms grant access to their airplane patents to all other members. Members paid an initiation fee to the MAA and $200 in royalties on each aircraft that they built. The royalties were allocated between the Wright and Curtiss firms on a 3.35:1 ratio until the expiration of the Wright and Curtiss patents and/or an accumulated royalty payment of $2 million to each firm. MAA members could license their patents to nonmember firms on terms no more favorable than those granted to members.

The original MAA agreement was signed on July 17, 1914 by eight U.S. firms: Aeromarine; Burgess; Curtiss Aeroplane; L.W.F. Engineering; Standard Aero; Sturtevant Aeroplane; Thomas-Morse Aircraft; and Wright-Martin.[22] The Dayton Wright Corporation, a firm founded in 1914 by a group of Dayton industrialists and engineers that employed Orville Wright as a consultant, was added to the agreement a few months later (Bittlingmayer, 1988, n. 21, p. 232). All patents on airplane structures, excluding instruments and engines,[23] were to be made available to all other members of the MAA under the terms of the 1917 agreement. Provisions were included in the MAA agreement for royalties for patents if the patent "…secures the performance of a function not before known to the art or constitutes an adaptation for the first time to a commercial use of an invention known to the industry to be desirable of use but not used because of lack of adaptation, or is otherwise of striking character or constitutes a radical departure from previous practice, or either the price paid therefor or the amount expended in developing the same is such as to justify such compensation." An MAA arbitration board determined the eligibility of patents for such treatment and determined royalties. By 1933, total royalty payments amounted to $4,360,000, with $2 million of that total allocated respectively to the Wright and Curtiss firms, which by 1929 had merged to form Curtiss-Wright.

An important provision in the MAA agreement, reflecting the involvement of federal policymakers in its negotiation against a backdrop of imminent U.S. entry into a European war, covered patents that resulted from government-funded research or related activities.

[22] Most of these original signatory firms were merged or acquired in the subsequent decades.
[23] The agreement covered "heavier-than-aircraft, using wing surfaces (and including) power plant appurtenances…but not to include the engine and engine accessories." (Bittlingmayer, 1988, n. 21, p. 232). With the exception of Curtiss-Wright, formed from the 1929 merger of Wright Aeronautical and the Curtiss Aeroplane Co., none of the members of the MAA produced both airframes and engines.

The agreement provided that all MAA members could use any patent resulting from government-funded work on a royalty-free basis, regardless of whether or not the patent holder was an MAA member. MAA members could obtain title to any patent resulting from their work on government contracts, but federal agencies retained a royalty-free license to any such patents. Moreover, as Ferguson (2000) points out, during the interwar period, the U.S. military frequently awarded production contracts for new aircraft to firms other than those who designed the aircraft, regardless of their patent positions:

> The MAA's reach did not cover manufacturing technologies, though. Nor did it have much influence on military designs, since during the interwar years the U.S. Navy and Army Air Corps could award production contracts to any manufacturer they chose—regardless of the design's origin. Though not the original intention of the military's policy, this was a powerful means for spreading leading-edge aircraft design knowledge across the nation's industry. (Ferguson, 2000, p. 263)

The upsurge in federal funding of R&D and production contracts in the U.S. aircraft industry that occurred after 1940, therefore is likely to have further weakened any MAA member's ability to use patents to exclude competitors and restricted patent-based competition within the aircraft industry. At least some data on patenting in the post-1945 period are consistent with this characterization of the role of MAA patents in aircraft technology. According to Bittlingmayer (1988), a total of 121 patents in the "aerospace" patent class (244) were added to the MAA agreement during 1968-72, representing 7.8% of all U.S. patents issued in this class during the period.

A different account of the effects of the Wright-Curtiss patent litigation and the subsequent formation of the MAA can be found in Katznelson and Howells (2014), who argue that innovation and entry in the pre-World War I U.S. aircraft industry were not harmed by these disputes. Katznelson and Howells (2014, p. 45) further claim that existing regulations meant that U.S. firms were able to meet the needs of the U.S. and foreign governments for military aircraft without any resort to a patent pool, and that "The MAA Agreement was not the voluntary and privately-negotiated agreement that a typical patent pool is usually understood to be. It is better understood as a technology transfer and supply agreement that served the government's perception of its own interests and not the interests of patentees...it was a government-instigated "buyers' cartel," the basic design of which is familiar in contemporary examples."

This portrayal of the U.S. aircraft industry during the 1908-1914 period and the MAA's formation, it is worth noting, is virtually unique within the large literature on these topics, a point that the authors acknowledge. Their dismissal of the Wright-Curtiss patent disputes as an obstacle to the development of the U.S. industry is shared by Crouch (2000), who is cited by the authors as claiming that the U.S. industry during this period was innovative.[24] But these authors' characterization of Crouch's assessment of the U.S. aircraft industry is contradicted by his statement that the industry had fallen behind those of Europe during 1908-1914:

The American Glenn Curtiss had won the first James Gordon Bennett race, staged as part of the Reims meet in 1909. By 1913, the U.S. could not field a competitor for the same race…The airplane, born in America, had come of age in Europe—and the gap would grow much wider during four years of war. (Crouch, 2000, p. 290).[25]

[24] "Besides listing evidence of technological advance in aircraft design in the decade up to the First World War, Crouch points out that the target of the Wrights' patent litigation, Curtiss and his manufacturing companies, had "overwhelming" commercial success in the US market for aircraft manufacture (Crouch, 2000: 294)…" (Katznelson and Howells, 2014, p. 8).

[25] A similar statement may be found in Rae (1968, p. 1): "Apart from the achievement of the Wrights, the only major American contribution to aeronautical progress in the prewar period was Glenn Curtiss' pioneering work with seaplanes."

Katznelson and Howells further claim that the U.S. aircraft industry was growing rapidly, but the bulk of their evidence on entry and aircraft output focus on the period between 1914 and 1916, when wartime demand from European governments and, eventually, the U.S. government for military aircraft had expanded greatly. Nowhere do these authors address the point, emphasized by Lorell and Levaus (1998), that no U.S. firm designed and developed a fighter aircraft that was deployed during World War I—the majority of U.S. firms' wartime aircraft output used French and British airframe designs. Having dismissed claims that the U.S. aircraft industry was in fact lagging behind those of Europe, Katznelson and Howells also do not present a clear explanation for the motives of U.S. policymakers that underpinned their support for the MAA, beyond referring to the "…sometimes eccentric beliefs about patents, and the Wright patent in particular…:" (2014, p. 44) that (All? Some?) U.S. policymakers held. The authors also do not acknowledge the point (emphasized in Crouch, 2000) that claims in the Wright patent were narrowed by courts in France and Germany, another factor that may have contributed to the divergent development of the European and U.S. aircraft industries during this period.

The "revisionist" view of the MAA set forth in Katznelson and Howells (2014) thus appears to rely on a selective use of evidence and an incomplete portrait of the motives for the formation of the pool. Moreover, the reasons for the formation of the MAA may be less important that the fact that the U.S. aircraft industry operated such a pool for nearly 60 years. Separating the effects on the pre-World War I U.S. aircraft industry of the Wright-Curtiss patent disputes from the effects of other factors, such as the U.S. military's failure to develop a more coherent and well-funded strategy to support the U.S. military aircraft industry during the pre-World War I years, is virtually impossible with the available evidence.[26] Once the MAA was created, the role of patents in this industry was transformed, and this role was further affected by the expanded federal role in military aircraft R&D and procurement that emerged by the 1930s.

The MAA agreement was the target of a U.S. Justice Department challenge filed in 1972, resulting in a 1975 consent decree that dissolved the patent pool.[27] It is difficult to discern significant anticompetitive effects of the MAA, although a counterfactual comparison is difficult at best. Inasmuch as during the post-1945 period, more than 80% of aerospace industry R&D investment was government-financed (Table 1), the majority of patents issued during that period to aircraft firms were available for use by MAA member and nonmember firms alike. Nor is there compelling evidence of significant change in patenting behavior by a leading U.S. aircraft firm after the dissolution of the MAA agreement, a topic that I discuss in the following section.

C. The effects of the MAA

The growth of patent pools in a number of fields of information technology during the past 25 years has sparked considerable new research on the effects of patent pools on innovation and patenting. What does this literature predict about the likely effects of a patent pool such as the MAA on the innovative behavior of member firms? In general, policy and economic theory tend to support the creation of patent pools when competing entities hold patents that need to be combined to create a product and that are ruled to infringe on one another—very similar to the situation in the U.S. aircraft industry in the early 20th century depicted by many

[26] Crouch (2000) argues that the lack of such a U.S. government military strategy, rather than the patent disputes, was the key reason for what he describes as the loss of technological leadership in aircraft by U.S. firms.

[27] The 1975 Consent Decree listed 20 firms among the defendants: Aeronca, Beech, Bell Aerospace, Boeing, Cessna, Curtiss-Wright, Fairchild Hiller, General Dynamics, Goodyear Aerospace (which requested to be removed as a defendant on the grounds of having no patents in the pool), Grumman, Kaman, LTV, Lockheed, Martin-Marietta, McDonnell Douglas, North American Rockwell, Northrop, Piper, Ryan, and United Aircraft (Bittlingmayer, 1988, n. 29, p. 234).

scholars. Nevertheless, a broad patent pool of the type exemplified by the MAA raises the risk that innovation by member firms will decline, since the returns to investment in R&D yielding innovations in the technology covered by the pool are shared with other members of the pool rather than being captured in their entirety by the investing firm (Katznelson and Howells, 2014, make this argument). These disincentives for firms to pursue innovation in the technologies covered by the patent pool may increase their investments in technologies related to their products that are not covered by the patent pool, since the returns to these R&D investments presumably are more easily captured in their entirety. Alternatively, member firms may pursue nonpatent-based means to exclude others from their inventions.

A recent paper by Lampe and Moser (2010) on the sewing-machine patent pool of the late 19th century, which covered patents linked to a specific subset of stitching technologies in this industry, concludes that overall innovation among member firms declined somewhat after the pool's formation, and that member firms increased their patenting in fields not covered by the pool. These findings are broadly consistent with the arguments above about reduced incentives for member firms to invest in R&D related to the fields covered by the pool, while potentially expanding their innovative activity in fields outside of the pool. In the case of the MAA patent pool, one might predict that the intensity of patenting by member firms in aircraft technology would decline during the life of the pool, that inventive activity in fields not covered by the pool would increase, and that nonpatent means for protecting firms' intellectual property would grow.

One simple test for the effects of MAA membership on member-firm inventive activity (not innovative activity) compares patenting before and after the dissolution of the Association in 1975. Unfortunately, we lack a sufficiently detailed time series on assigned patents and firm-funded R&D investment (recognizing that firm-funded R&D accounts for little more than 10% of aircraft industry R&D investment during the 1945 – 82 period) to compare the "patent propensity" (patents/constant-dollar R&D investment) of MAA member firms before and after the 1975 dissolution of the patent pool. Figure 10 displays trends in the patent propensity of one MAA member firm, the Boeing Corporation, for 1976-2012. The data in Figure 10 include patents in U.S. patent classes not covered by the terms of the MAA. The time series begins one year after the formal dissolution of the MAA, but covers issued patents and therefore should capture the effects of R&D investment and patent applications that were undertaken before 1976. Boeing, a longtime member of the MAA, was chosen for this calculation because it historically has been one of the less widely diversified U.S. aircraft firms, although the firm does patent outside of the aerospace field.

If the predictions of the Lampe-Moser analysis of the sewing-machine patent pool apply to MAA member firms, we anticipate an increase in the "patent propensity" of Boeing and other members after 1976 in the patent classes covered by the MAA, which should increase the corporate propensity. In fact, however, the time series in Figure 10 gives little if any indication of an increase in the corporate patent propensity of Boeing after the dissolution of the MAA, and the average patent propensity for the firm is below the overall patent propensity of U.S. manufacturing firms during at least the early years of the post-MAA period (Hall and Ziedonis, 2001, estimate the average patent propensity of U.S. manufacturing at .3 - .4 during 1979-93). A related analysis compares the number of "design" and "utility" patents assigned to Boeing, on the assumption that design patents, not covered by the MAA, might represent a significant share of overall corporate patenting. As Figure 11 indicates, however, the number of design patents during 1989-2012 (the only period for which USPTO reports both design and utility patents assigned to corporations) is dwarfed by the Boeing utility-patent portfolio. It is of course possible that the 1989-2012 data fail to capture a different relationship between the number of utility and design patents assigned to Boeing during the MAA's existence, and this possibility should be examined in future research. But there is little indication from Figure 11 that design patents are an important overlooked area of patenting for this U.S. aerospace firm.

Similar data on the absence of any change in patenting behavior in the "aircraft" U.S. patent class (class 244) is displayed in Figure 12 (taken from Roland, 2000), the top panel of which plots total patents in class 244 during 1900-96. There is no evidence of any upsurge in total patenting after 1975 in these data, which do highlight increased patenting (in the aircraft patent class, not necessarily increased patents in this class that are assigned to MAA member firms) after the Wrights' public demonstration of their aircraft in 1908, as well increased patenting during the periods of the monocoque airframe innovations of the early 1930s and the introduction of commercial jet airliners in the late 1950s. The lower panel indicates that aircraft patents' share of overall U.S. patenting has declined since the early 1960s through the period shortly before and after the dissolution of the MAA. Patenting in class 244 accounts for less than .3% of total patenting by the 1990s.

These simple analytic tests thus reveal no evidence of significant change in the propensity to patent of one leading U.S. aerospace firm and MAA member in the immediate aftermath of the dissolution of the patent pool, and provide no support for the hypothesis that the MAA's existence and dissolution affected overall patenting in the aircraft technology class. There are at least two other potential effects of MAA membership that may be observable through a more extensive analysis of the patents assigned to MAA member firms. First, the possibility exists that MAA member firms invested more heavily in invention and innovation in technology fields not covered by the MAA, e.g., outside of the 244 patent class.[28] This hypothesis, which is similar to one tested by Lampe and Moser (2010) in their analysis of the sewing-machine patent pool, effectively predicts that membership in a patent pool causes firms to reallocate their inventive effort to fields not included in the pool, for reasons noted earlier. An analysis of the allocation among patent of MAA member firm-assigned patents before and after the pool's dissolution could test for significant shifts in the shares of different patent classes in member-firm patent portfolios. This hypothesis predicts that the share of 244-class patents should increase in member-firm patent portfolios after 1975.

A second potential patent-based analysis of the effects of the MAA on the inventive activity of member firms uses citation analysis of the "quality" of the 244-class patents assigned to member firms before and after the pool's dissolution. Lampe and Moser (2010) showed that the pace of innovation in sewing machines slowed somewhat after the formation of this industry-wide patent pool. Although citation-based indicators of patent "quality" (i.e., the rate at which other firms or entities refer to MAA member-firm patents after their issue) do not precisely capture changes in the rate of innovation, it is plausible that changes in average citations to patents are correlated with changes in the quality of these patents and their associated effects on the pace of innovation. Citation-based measures of the quality of 244-class patents assigned to MAA member firms before and after the dissolution of the patent pool, analyzed with a "control sample" of patents from the same patent class assigned to non-MAA member firms that cover the same time period, could shed light on the extent of these hypothetical effects of pool membership on the quality of member firms' inventive efforts.[29] The Lampe-Moser analysis suggests that the quality of MAA member-firm patents

[28] The only MAA member firm to produce both engines and airframes during the MAA's existence was Curtiss-Wright, as I noted earlier. A test of this hypothesis accordingly could compare the rate of patenting by Curtiss-Wright in engines, as opposed to the technologies covered by the MAA, during and after the MAA's existence. Curtiss-Wright exited the design, development and production of airframes in 1965, following the failure of its X-19 prototype short-takeoff turboprop aircraft. The firm also failed to develop a commercially successful turbojet engine during the 1950s and 1960s. By 1975, the year in which the MAA was dissolved, Curtiss-Wright was a diversified industrial firm producing machinery for applications in numerous industries, and its primary aerospace-related production activities dealt with components, not complete airframes or engines.

[29] Another test of the effects of MAA membership on the rate of innovation would attempt to develop direct measures of the rate and significance of innovations in aircraft technology with the rate and significance of innovations in aircraft engine technology, a field not covered by the MAA. If the "innovation-depressing" effects of MAA membership are significant, one might hypothesize that the pace of innovation in aircraft technologies lagged behind that of aircraft engine technologies. Unfortunately, there are no widely accepted measures of the pace and significance of innovations in these two fields that would support such a comparison.

in class 244 should improve, by comparison with the control-sample patents, after the dissolution of the MAA.
It is also possible that the MAA's existence discouraged reliance in aircraft technologies by member firms on patents, which had to be shared with all other members, in favor of other means of protecting their intellectual property, such as secrecy.[30] Although there is abundant evidence of strong firm-specific differences in design, fabrication, and production methods that impeded the exchange of technical information and/or collaboration in wartime production of military aircraft during World War II,[31] there is little public evidence of litigation among U.S. aircraft firms over trade secrets. This potential effect of the MAA on member firms' innovation-related activities thus is another hypothesis that is plausible, but for which any evidence in support or contradiction of which is virtually nonexistent.

The effects of the MAA on member firms' innovative activity thus remain ambiguous, although a number of issues need additional research. But the limited evidence of such effects should not be surprising, in light of the fact that firm-funded R&D investment by member firms accounted for a relatively modest share of industry-wide investment in innovation-related activities during most of the existence of the MAA. Unlike sewing machines, the majority of the R&D investment that membership in a patent pool might affect was underwritten by public funds. The MAA patent pool thus differs from recent product-specific patent pools in technologies such as DVDs or CDs, or from other industry-wide patent pools such as the Association of Licensed Automobile Manufacturers, in that public rather than private funds supported the majority of innovative activities of member firms. The predicted effects of patent-pool membership on innovation are ambiguous when member firms do not account for the majority of R&D investment.

D. Why did U.S. commercial aircraft firms patent?

As I noted earlier, the nature of aircraft technology is such that patents provide limited protection at best for firms' intellectual property. Moreover, the presence of a comprehensive patent pool covering "aircraft technology" within the U.S. aircraft industry for nearly 60 years further discouraged firms' incentives to pursue patents on inventions, particularly when secrecy seemed to be an effective means to protect at least some types of intellectual property (notably, production processes). Finally, the presence of the federal government as an important source of R&D investment and a major market within the U.S. aircraft industry for most of the 20th century undermined the effectiveness of patents, since patents based on federally funded R&D could be licensed by the federal government on a royalty-free basis and since firms were allowed to use competitors' intellectual property for production of aircraft for military uses.

In spite of these factors that tend to weaken the importance of patents within this industry, the fact remains that U.S. commercial aircraft firms did file for patents before, during, and after the MAA. As I pointed out earlier, some evidence suggests that the "patent propensity" of at least one large U.S. aircraft firm in fact was lower than the average for overall U.S.

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[30] In his discussion of collaborative production of U.S. military aircraft during World War II, Ferguson (1996, p. 108) noted that "If significant aircraft design patents were to be shared under the MAA, it became all the more important to retain a competitive advantage in production techniques."

[31] Ferguson (2000, p. 259) described the problems encountered by wartime contractors in production collaboration as rooted in part in these firm-specific differences in practices, few if any of which were codified: "The difficulty of exchanging engineering knowledge [among military-aircraft producers] had less to do with legal and proprietary boundaries than it did with technological cultures, a firm's unique methods of designing and producing aircraft. In some cases these practices were so different that even when firms attempted to manufacture identical products, they were simply unable. While individual components of a manufacturing system might be adopted across firms, production systems themselves remained highly localized and the result of idiosyncratic philosophies. An examination of the design and manufacturing process reveals that design information was not only lost or changed as it proceeded from the drawing board to the factory floor, but that it continued to be created along the way."

manufacturing during the 1970s and 1980s, but the fact remains that Boeing and other U.S. aircraft firms were issued numerous patents. How can this apparent anomaly be explained?

There are at least three factors that may have encouraged patenting by U.S. aircraft firms. First, firms that were members of the MAA did not face significant threats from patent-infringement suits filed by other member firms, but such protection against patent litigation did not apply to nonmember firms. And as Bittlingmayer (1988) noted, non-MAA members appear to have accounted for a substantial majority of U.S. patenting in aircraft in the late 1960s and early 1970s, and may have been equally important patenters during other phases of the industry's evolution. U.S. aircraft firms that were members of the MAA accordingly could benefit from patents on their core technologies, both by avoiding potentially costly litigation and worse yet, injunctions that could paralyze expensive manufacturing facilities, and by preserving their "freedom to invent" in broad fields of technology.

Just as MAA member firms were not "immunized" against potential litigation from domestic competitors, foreign firms similarly were not bound by the terms of the MAA. In view of the importance of international markets for their products through most of the U.S. aircraft industry's history, filing U.S. and equivalent foreign patents may have been an important means to reduce the risks of infringement and/or litigation by foreign firms.

Finally, and in common with other large, knowledge-intensive U.S. firms, U.S. aircraft firms filed for patents as a means of assessing and comparing the performance of their in-house designers and engineers. Patents are costly to prosecute, but the extensive review of their claims and originality mean that they represent a useful and fairly rigorous "metric" for assessing the performance of a firm's R&D staff. Moreover, many U.S. aircraft firms provide modest compensation to employees who file successfully for patents that typically are assigned to their employers under provisions of their employment contracts.[32]

All three of these factors influenced the patenting behavior of U.S. aircraft firms during the industry's development, although definitive evidence on their relative importance, or the overall significance of U.S. firms' patenting strategies, is limited. One additional source of information on the patenting strategies of U.S. aerospace firms (including many non-MAA members) is the 1994 survey of corporate R&D managers summarized in Cohen et al. (2000), which reports results for "complex product" industries, such as aerospace, manufacturers of products that are integrated systems incorporating numerous technologies. The role of patenting in "complex products" industries may differ from patenting in "discrete product" industries, which include chemicals and pharmaceuticals firms whose products often rely on intellectual property consisting of one or more molecules or catalysts.

Cohen et al. (2000) report results on the use of patents by aerospace firms (a total of 37 respondents) for "cross-licensing" strategies, i.e., patenting strategies that seek to use patents as "bargaining chips" in negotiations with other firms. The definition of "cross-licensing" strategies employed in the paper excludes the use of patents as a means to capture licensing revenues. According to the survey results, 11.3% of aerospace firms seek patents in pursuit of "cross-licensing" strategies, far below the average of 54.8% for all "complex products" industry respondents in the Cohen et al. (2000) survey.[33] A second patenting strategy, "Fences," refers to the use of patents to block rivals from patenting related inventions by building a patent "fence" around substitute or complementary technologies needed to invent in related fields—patent "fences" in complex product industries often target complementary technologies because of the products of these

[32] Writing about patenting by U.S. aircraft firms during World War II, Ferguson (1996, p. 114) noted that "Typically companies rewarded employees in three ways: an initial award of $5-10 for a patent suggestion, a subsequent award of perhaps $25-50 if the patent was successfully filed, and finally, 10 to 30 percent of any royalties that might be collected."
[33] The authors weight responses by the number of patent applications that each firm has filed during 1994.

industries require a large number of such inputs. According to Cohen et al. (2000), 16.4% of aerospace respondents cited that patent "fences" as an important motive for patenting, above the average of 10.6% of respondents in all complex product industries (As before, the authors define the "fences" strategy to exclude the use of patents as a means of pursuing licensing revenues). A final patenting strategy whose importance is assessed in the survey is "player," which refers to a patenting strategy that mixes cross-licensing and patent fence motives (i.e., firms seek to become "players" in negotiations with competitors over intellectual property, regardless of the precise objectives sought through such negotiations). This mixed motive is relatively unimportant among the aerospace respondents, accounting for slightly more than 9% of responses, well below the average of almost 45% of complex product industry respondents reporting that this strategy is important in their patenting behavior.

The survey results in Cohen et al. (2000) thus suggest that building patent "fences" was the most important strategic motive for patenting in the U.S. aerospace industry as of the early 1990s, and that this motive was more important for aerospace firms than for other firms in "complex product" industries. It is interesting to note that the use of patents to block rivals is similar to the behavior that most observers claim was characteristic of the U.S. aircraft industry before the formation of the MAA, when the Wright and Curtiss groups each used their patents to block entry and/or innovation by rivals. The lack of evidence on significant change in the patenting behavior of U.S. aircraft firms after the dissolution of the MAA, recognizing that any evidence on this issue is very limited at present, also suggests the possibility that a form of organizational "path-dependence" may have translated into relatively modest patenting activity after 1975. But this issue needs further research.

VIII. International diffusion of commercial aircraft technology

Aircraft design and production capabilities were established quickly in other high-income economies besides the United States after the Wright brothers' demonstration of the feasibility of powered flight in the early 20th century. Within the first decade of the 20th century, Alberto Santos-Dumont and Louis Bleriot were piloting aircraft of their own design in France, and the first prototype of a four-engine passenger transport (later modified to serve as a military bomber) was designed and produced by the Russian aeronautical inventor Igor Sikorsky in 1913. European governments' growing investment in military aircraft development and production, combined with the reluctance of U.S. policymakers to mobilize for war, meant that by 1914 the production of aircraft by European nations considerably outstripped that of the United States.

There is very little quantitative or other information on the channels through which inventors and engineers learned from one another during the 1903 – 1914 period. As I noted above, one important means for information transmission was the exhibition flights conducted throughout Europe and the United States during this period by the Wright brothers and other inventors. The rapid growth of aircraft design and production activities in Europe in particular suggests that international diffusion of aircraft design and production capabilities during the early 20th century was not impeded by patent-related or other obstacles. Instead, the nearly simultaneous development of aircraft design and production in nations ranging from Tsarist Russia to Germany, Britain, and France appears to have relied on R&D and training in domestic universities, technical institutes, and government laboratories, as well expanded investment by firms eager to win government contracts for military aircraft. The rapid diffusion of aircraft design and production activities among European nations was in part a reflection of the fact that aircraft "manufacture" during 1908-12 the time was essentially an artisan activity involving manual assembly and small production volumes. These characteristics of aircraft production processes began to change with European governments' growing investment in military aircraft development and production in the years immediately prior to World War I.

A similar pattern of relatively unrestricted flows of technical knowhow and production capabilities among the high-income economies (now including Japan) appears to have characterized the 1919-40 period. Indeed, as has been pointed out elsewhere, the United States was the source of important innovations in commercial aircraft during this period, even as U.S. engineers and scientists failed to advance aeronautical theory or the jet-propulsion advances of other nations. As I noted earlier, U.S. backwardness in aeronautics began to change during the 1930s, partly as a result of the emigration of German scientists of the caliber of von Karman to the United States, but genuine progress in aeronautics required the large-scale disclosure of German technical designs and emigration of German researchers to the United States after 1945.

The history of the aircraft industry during the 20th century thus is characterized by the operation of multiple channels for international and domestic transmission of technical data, scientific theories, and design knowhow. In the earliest years of the industry, amateur experimenters and scientific researchers appear to have shared information liberally. By 1908-09, this channel of "open disclosure" was supplemented by the efforts of young aircraft firms to exhibit their designs in traveling shows and increasingly, through organized air races. In addition, however, these firms began to pursue innovation in-house and to protect their intellectual property. World War I provided a powerful impetus to these intrafirm innovative efforts, the results of which disseminated in some cases through licenses (U.S. production of fighter aircraft for the British and French militaries) and in other cases was restricted. But a vigorous international scientific community of researchers in academia and government remained active before and after World War I, and disseminated their technical results through conferences and publications. Such dissemination of codified scientific knowledge, however, was not always sufficient for lagging nations such as the United States to recognize the possibilities of advanced airframe and propulsion technologies for application in military and civilian aircraft. A key channel for international knowledge transfer during most of this period remained the movement of people.

A. International diffusion of aircraft production capabilities and collaborative ventures in aircraft development and production

The demonstration of the destructive power of military aircraft during World War II further motivated governments to develop or seek to sustain military-aircraft design and production capabilities. During the post-1945 period of Cold War, the United States pursued extensive technology-sharing and "co-production" agreements with NATO allies and Japan to (partially) standardize the weapons used by the United States and military allies, and to support the domestic military-aircraft production capabilities of these nations. These military-aircraft production capabilities in some cases supported entry into commercial aircraft and the growth of regional collaboration in such commercial ventures as Airbus. Nonetheless, the large commercial aircraft segment of the global industry has since 1960 been characterized more by exit (often through merger) than entry, with no more than two global producers of airframes (Boeing and Airbus Industrie) active in the sector since the 1990s.

Although commercial airlines began operation throughout low- and middle-income economies early in the 20th century (often as part of colonial empires), none of these nations has yet successfully entered the independent design and production of large commercial aircraft. Beginning in the 1990s, firms in China and South Korea have become important suppliers of components to the leading producers of large commercial aircraft (See U.S. International Trade Commission, 1998), but none of these firms has entered the global market for large commercial aircraft as an independent producer. Nor have firms from these or other nations entered the independent design and production of turbofan engines, although their role as component suppliers has grown.

Several factors explain the exit of established producers of large commercial aircraft and underpin the lack of entry by new firms. First, the financial costs and technical risks of new-product development in large commercial aircraft are high and exceed the resources of all but the largest established firms. Indeed, industrial-economy governments since 1945 frequently have played an important direct (through state ownership, or the bailouts of Rolls Royce and Lockheed) and indirect (as in the implicit subsidies provided by NASA and military aeronautics research for U.S. firms such as Boeing, or the "launch aid" provided by European governments to the various members of the Airbus consortium) role in stabilizing the finances of established producers of airframes and engines.

The cost structure of new-product development projects in large commercial aircraft also is "lumpy," in that the high fixed costs of developing a new airframe or engine can only be recovered through large production runs that extend over decades. This need for large production volumes of the original and derivative designs mean that access to global markets is essential, and it is no longer feasible for a new producer to pursue an "infant industry" strategy that seeks first to penetrate its domestic market before entering global markets. With the possible exception of China, no single domestic market in today's global economy is large enough to support an "infant industry" entry strategy. Instead, established producers seek to penetrate the broadest possible cross-section of markets for their products as quickly as possible.

Another factor contributing to the exit of experienced producers and the lack of entry by new firms in the large commercial aircraft industry is the need for producers of airframes and engines to maintain large global product-support networks, supplying parts, mechanical and technical advice, and occasionally, maintenance of their products in the field. The high purchase price of airframes and engines means that the financial penalties associated with an aircraft that is taken out of service because of mechanical or other problems are large, and airlines rely on airframe and engine firms to minimize such unscheduled "downtime" through rapid responses to operating problems throughout the world. Airframe and engine producers also use their global product support operations to gather information on the performance of new products and apply such information to modifications of designs and operating instructions. The fixed-cost characteristics of the operating expenses of these product support organizations provide an incentive for producers of both airframes and engines to offer a "full line" of products that spans different segments (e.g., different passenger capacities, operating ranges) of the large commercial aircraft market. A new entrant thus must develop a credible, global product support network and introduce a range of different products to defray the high fixed costs of such a network. The need for such product-support capabilities operates as another barrier to entry by new firms into the global large commercial aircraft market.

In addition to contributing to the exit of established firms, these characteristics of the modern large commercial aircraft market also have contributed to the growth of interfirm collaboration in the airframe and engine industries, collaboration that typically spans national boundaries. Since the early 1970s, the product development and production processes within the U.S. commercial aircraft industry have been transformed from activities largely carried out within U.S. firms to collaborations among U.S. and foreign firms (Mowery, 1987). With few exceptions, no large commercial aircraft or engine introduced since 1975 has been developed or manufactured solely by one of the major U.S. producers.

The transformation of new-product development and production organization within the industry was one effect of three broad changes in the policy structure that influenced the post-1945 development of the U.S. commercial aircraft industry. Deregulation of domestic air transportation in 1978, a decline in the commonality of military and civilian aircraft technologies, and continued growth in development costs to make market demand for new commercial aircraft more uncertain and risky, all increased the financial risks faced by U.S. commercial aircraft firms.

The growth of international collaboration in the large commercial aircraft industry also was motivated by change in the structure of global demand for these products. U.S. aircraft firms, for example, have had to adapt their product-development strategies to the declining share of demand for large commercial aircraft accounted for by the United States relative to the rest of the world (especially the industrializing nations of East Asia and China). Between 1950 and 1970, U.S. airlines purchased 67 percent of the aircraft produced by U.S. firms, and the United States accounted for 57 percent of total world revenue passenger miles flown in 1971. During the 1970s, however, reflecting demographic factors as well as slower U.S. economic growth, air travel in the United States grew at an annual rate of 5 percent, well below the average growth rate of 9 percent in other regions. Between 1977 and 1982, only 40 percent of orders for new commercial aircraft originated with U.S. carriers.

International collaboration in commercial aircraft has focused on product development and manufacturing, reflecting the fact that the critical competitive assets are product design and manufacturing expertise. Access to foreign markets, risk-sharing, and access to low-cost capital for new product development (the low cost of such capital frequently reflects direct or indirect public subsidies that are part of programs to build up national aerospace industries) are the major motives for collaboration between U.S. and foreign commercial aircraft firms. Collaboration can enhance market access because foreign markets for commercial aircraft are characterized by heavy government involvement, often as owners of airlines or aerospace firms. Foreign governments in many cases see collaboration with U.S. or European firms as a means of strengthening domestic aerospace industries and/or as a means of establishing new capabilities in this sector.

Although most collaborative ventures between U.S. and foreign aerospace firms have involved significant outflows of U.S. firms' expertise and technological knowhow, patents and licensing have played a relatively minor role in the structure of these collaborative ventures. Nor is the technology transfer that has taken place within these collaborations exclusively a one-way outward flow from U.S. to foreign firms.

1. Brazil's entry into commercial aircraft production: Embraer

One of the few examples of successful entry into the global commercial-aircraft market by a new producer from a middle-income economy is that of Embraer, the Brazilian producer of commuter, business, and regional jet aircraft. Significantly, Embraer's commercial product line has focused on smaller aircraft, and the firm has not attempted to enter the large commercial aircraft market. Nonetheless, Embraer's relative success is noteworthy, and a brief summary of its history highlights some of the points made earlier on the nature of international technology flows and the role of domestic markets and international collaboration in commercial aircraft.

The Brazilian aircraft industry has a long history. A wealthy Brazilian expatriate then living in France, Alberto Santos-Dumont popularized the new technology of aircraft in Europe before ending his flying career in 1911, and the value of aircraft for internal transport and defense of its vast landmass meant that the Brazilian military has long been interested in promoting a domestic aircraft industry. The large scale of Brazil's domestic market for small aircraft meant that a producer of small aircraft could survive financially from domestic sales. Beginning in the 1930s, the Brazilian government provided direct and indirect support (e.g., procurement orders) for various ventures in the design and production of small aircraft. The Brazilian military also supported the establishment of the Centro Tecnico Aerospacial (CTA) in the late 1940s to coordinate R&D on aeronautics. A technical institute devoted to training aerospace engineers, the ITA, was established in 1950 under the leadership of former MIT

Professor Harbert Smith, underscoring once again the role of scientific migrants in diffusing knowledge in this sector.
The first Brazilian aircraft firm that proved to be financially viable was Embraer, established in 1969 with the support of the military government then in power in Brazil. Embraer initially produced small turboprop commuter aircraft, notably the Bandeirante, which was purchased in large quantities by the Brazilian military and eventually enjoyed success in export markets. The firm subsequently expanded its commercial aircraft line to include regional passenger jets, such as the Embraer 190, with seating capacity up to 120 passengers. Embraer also has produced several military trainer and fighter-trainer aircraft, including the Xavante, produced under a licensing agreement with the Italian firm Aermacchi, and small general-aviation aircraft through a collaborative agreement with Piper Aircraft of the United States.

The collaborative agreements between Embraer and non-Brazilian producers, such as Piper and Aermacchi, have been important channels for the transfer to Embraer of production technologies, but these agreements do not appear to have resulted in substantial inward transfers of design expertise to Embraer, perhaps reflecting the fact that Brazil's longstanding public investments in aerospace research and training had created strong domestic capabilities. Indeed, the agreements with Piper Aircraft covering Embraer's production of its general-aviation designs were finalized after the introduction of the Bandeirante, a larger and more complex aircraft design. Instead, the Embraer-Piper agreements, as well as the Xavante agreement with Aermacchi, appear to have served as vehicles for these foreign firms to penetrate the large Brazilian market by teaming with a Brazilian firm with strong ties to government and military policymakers. Embraer benefited by broadening its product line and (as a firm with strong ties to the Brazilian government and military) expanding its production capacity.

The case of Embraer thus is one of a domestic aircraft industry developing on a foundation created by a longstanding government investment in research and training infrastructure. Rather than using international collaborations to transfer design and other technical skills to Brazilian firms, Embraer has used its position in the large Brazilian domestic market as well as its production facilities and capabilities to attract the participation of foreign firms in the Brazilian manufacture of established designs and some collaborative development of new aircraft (e.g., the Xavante). Embraer's aircraft typically have used avionics and engines from non-Brazilian producers, illustrating the global nature of the market for aerospace components. The inward technology transfer that has occurred through a succession of collaborative agreements between Embraer and foreign producers appears to have been somewhat limited and if anything has followed, rather than catalyzing, the growth of significant domestic aerospace design skills within Brazil. Finally, although formal licensing agreements have been a part of many of the collaborative agreements between Embraer and foreign firms, these agreements include much more than patents alone, focusing in particular on production knowhow. The Embraer case also highlights the importance of a large domestic market as a "platform" for entry by new firms into the global aircraft industry, even as this case also is one of entry into markets other than those for large commercial aircraft.

B. Other measures of international diffusion

An alternative definition and associated indicators of the diffusion of the "breakthrough innovation(s)" represented by aircraft focus on the growth of air travel, particularly the diffusion of air travel from high- to middle- and low-income nations. Unfortunately, very little comprehensive data on the regional distribution of air travel (e.g., revenue passenger-miles or –kilometers) covers the decades before the 1960s. One source of such data, Davies (1964), notes that the number of scheduled commercial airlines grew from 27 in 1919 to 100 by 1929 and 200 by 1945; as of 1961, his tabulation concluded that roughly 260 scheduled airlines were in existence, and the region accounting for the largest number (70-75) was

Latin America. According to Davies (1964), the eight “leading air transport nations” in the world in 1928, ranked by the number of passengers carried by each nation’s airlines, were Germany; Canada; the United States; the United Kingdom; France; Italy; the Netherlands; and Poland, with estimated passenger traffic ranging from 100,000 in Germany to roughly 5,000 in Poland. By 1930, Davies estimated that within Europe, Germany accounted for more than 120,000 thousand passengers, France for roughly 55,000, Italy for 41,000, the United Kingdom for 30,000, and the Netherlands for roughly 18,000. Within Europe, German passenger traffic had risen to roughly 280,000 by 1939; the USSR accounted for roughly 270,000; the United Kingdom for roughly 220,000; the Netherlands accounted for roughly 165,000 passengers; and Italy for 120,000. The 1930s were a period of rapid growth in overall European passenger volumes, especially in the Soviet Union, while the share of European air travel accounted for by French airlines declined. By comparison, the U.S. Civil Aeronautics Board reported in its *Statistical Handbook of Civil Aviation: 1948* that U.S. airlines carried more than 1.7 million passengers in 1939, although this statistic includes some double-counting of passengers carried by more than one airline on a given route.

A global portrait of the evolution of international air traffic among regions of the global economy, based on the national “identity” of carrier airlines, is contained in Figures 13 – 14, which use data from Davies (1964) to depict the regional growth of passenger miles during 1929 – 61. Inasmuch as these data rely on the national affiliation of airlines, they are likely to overestimate the dominance of North America and Europe, home to a number of regional airlines serving foreign colonial empires and citizens of lower-income economies. Nonetheless, these data are the most comprehensive for the decades covered. Figure 14, which displays regional shares of global air traffic, clearly reveals the enduring dominance during the 1929-61 period of European and North American passenger travel, as well as the post-1945 increase in the European share of global traffic (13% in 1941, 33% in 1961) associated with the region’s postwar economic recovery. The effects of wartime also appear in the growth and decline of Latin America’s share of global air travel during and after the 1940s. Indeed, the shares of global air traffic accounted for by North America (71% in 1941, 51% in 1961), South and East Asia (4.4% in 1941, 3.3% in 1961), Australia and New Zealand (4.7% in 1941, 2.6% in 1961), and Latin America (6.6% in 1941, 6.1% in 1961) all declined during 1941 - 61. These data thus suggest that commercial air travel during the 1929 – 61 period was dominated by carriers located in high-income economies, with Europe experiencing a sharp decline and resurgence during and after the 1940s. The growth in Asian air travel that has transformed the global market for commercial airliners since the 1980s is absent from these data.

The early stages of a process of broader global diffusion in air travel are apparent in Figure 15, which utilizes data covering 1966 – 72 from various editions of the *Review of the Economic Situation of Air Transport*, published by the International Civil Aviation Organization (ICAO), to depict regional shares of global air traffic (International Civil Aviation Organization, 1977; 1980; 1983). Like the data in Davies (1964), these data use the national registration of carriers to calculate national shares, and exclude the U.S.S.R. and People’s Republic of China for the period covered. The post-1966 data from the ICAO extend the trend highlighted in Figure 14 in showing a continued drop in the share of global traffic accounted for by North America. But unlike its rise in Figure 14, the European share of global traffic drops through the 1966 – 72 period depicted in Figure 15, while that of Asia (which in this tabulation includes Australia and New Zealand) displays a sharp increase, more than doubling from 9.8% in 1966 to more than 20% by 1976. Overall, the trends depicted in Figure 15 indicate a gradual diffusion of air travel from the high-income regions of Europe and North America to the Middle East (whose share increases from 3.4% in 1966 to 4.8% by 1976), Africa (4.6% in 1966, 5.1% in 1976), and Latin America (6.1% in 1966, 6.9% in 1976), combined with more rapid diffusion to the Asian region.

A slightly different statistical perspective on the regional growth of commercial air transportation is provided in data published by the International Air Transport Association (IATA), a trade association comprising most of the world's airlines. Rather than using the nation of registration of the airline and aircraft to compute regional air traffic statistics, as did the ICAO and Davies (1964), the IATA's *World Air Transport Statistics* compile data on major international and domestic air travel routes. Since they focus exclusively on the regional travel routes, these data are less likely to be distorted by the complexities of airline nationality that are present in the other data discussed above. These asserted benefits, of course, come at a cost—the IATA data include only the more heavily travelled international travel routes. The IATA also reports passenger traffic only for its member airlines, a group that is subject to change over time and one that may exclude carriers from centrally planned or low-income economies during some years. A final limitation of the IATA data is the fact that the *World Air Transport Statistics* do not report data on regional route traffic prior to 1969.

Tables 16 – 17 respectively report the regional distribution of passenger-kilometers and the regional shares of total IATA passenger-kilometers for the 1969 – 75 period. Overall, these data highlight a decline in the dominance of global air travel by trans-Atlantic traffic (especially across the North Atlantic, linking North America and Europe) in both Figures, especially Figure 17. Also apparent in Figure 17 is the growth of air travel between Europe and Asia, and a significant decline in the share of global air traffic accounted for by intra-European travel. The data in Figure 16, which report traffic volumes, also highlight growth in travel between North America and lower-income regions such as South and Central America, as well as significant growth in traffic between Europe and Southern Africa, the Middle East, and North Africa.

Another indicator of the diffusion of commercial aircraft focuses on the geographic spread of commercial aircraft deliveries and change over time in the regional distribution of the stock of commercial aircraft within the global economy. Although the adoption of advanced aircraft is not necessary for a national to reap the economic benefits of expanded access to air travel for its citizens, it is likely that the geographic diffusion of commercial aircraft registered in low- and middle-income economies is correlated with such expanded access. Accordingly, I briefly summarize some of the relevant indicators on the diffusion of commercial aircraft by region.

Data compiled by Davies (1964) and the ICAO were used to construct Figures 18 and 19, which contains data on the evolution of regional commercial aircraft fleets by region during 1962 – 72, focusing on the change over time in the number and share of jet-powered airliners within each region's commercial air fleet. As was true of the air traffic data, the high-income regions of Europe and North America account for the largest shares of the global stock of commercial jet aircraft in both 1962 and 1972. Nevertheless, the data in the Figures contain evidence of rapid adoption of jet-powered aircraft in low- and middle-income regions of the global economy, notably Africa and the Asia/Pacific areas. All of the regions depicted in the Figures experienced significant growth in the share of their commercial air transport fleets accounted for by jet-powered aircraft, but the most dramatic increases in this share occurred in Africa (3% in 1962, 29.6% in 1972) and the Asia/Pacific region (4.6% in 1962, 34% in 1972). Both Europe and North America entered the period with jet-powered aircraft accounting for more than 10% of their commercial air fleets, but even these regions experienced substantial growth in the share of their fleets accounted for by jets (for Europe, an increase in this share from 12.8% in 1962 to 64.7% by 1972; for North America, an increase in this share from 14.4% in 1962 to 75.4% by 1972).

The rate of adoption of jet-powered aircraft, as well as the shares of jet aircraft in each region's commercial air transport fleet, are affected by factors other than economic development and/or the domestic demand for air travel. The domestic and international route structures of airlines obviously vary among the many nations represented in the data underpinning Figures 18 - 19, and it is far less economical to operate jet-powered aircraft on short routes with relatively light passenger loads. Small-capacity commercial jet aircraft were not widely produced during the period covered by these data, and their adoption in some commercial markets accordingly was not economically rational. The trends depicted in Figures 18 - 19 are broadly consistent with the air traffic data discussed above—by the 1970s, low- and middle-income economies had begun to expand as markets for air travel, and passengers had growing access to advanced commercial aircraft.

These trends are further corroborated by those in Figures 20 - 22, depicting the regional shares of deliveries during 1958 – 78 of aircraft produced by the dominant U.S. manufacturers of jet-powered commercial aircraft during this period, Boeing and McDonnell Douglas. The contrast between Figures 21 and 22, respectively showing the regional destinations of aircraft deliveries in 1958 and 1978, is particularly sharp, as the North American share declines from 100% in 1958 to 56.4% in 1978. Nonetheless, even by 1978, the high-income regions of North America and Europe dominate the deliveries of these U.S. firms' commercial jet aircraft, with their combined share of deliveries exceeding 73%, while Africa accounts for 4.5%. These data are distorted somewhat by the longstanding political and economic ties between nations in Africa and Asia and their former colonial overseers in Great Britain and France, both of which produced commercial jet aircraft for much of the 1958-78 period. But these Figures indicate a pattern of diffusion of advanced commercial aircraft that is consistent with other data on fleet composition and air traffic.

Summarizing these data on the diffusion of air travel and advanced commercial airliners, both global passenger air traffic and advanced commercial aircraft diffused primarily to high-income economies through the 1960s. Only during the 1970s do these data suggest that access to domestic and international air travel in low- and middle-income economies had begun to expand significantly, and the composition of domestic commercial airliner fleets similarly indicates the beginnings of a substantial market for jet-powered aircraft by the 1970s. This process of diffusion accelerated after the 1970s, and the resulting growth in importance of markets outside of the high-income economies of North America and Europe is associated with the development of the international risk- and cost-sharing collaborative arrangements for the development of new commercial aircraft discussed above.

IX. Conclusion

Innovation in commercial aircraft during the 20th century was a source of both dramatic technological advances and substantial economic benefits. Nevertheless, the modern commercial aircraft cannot be described accurately as a "breakthrough innovation." Instead, today's commercial aircraft incorporate a series of individually significant technical advances, such as the monocoque airframe or the turbojet engine, that have yielded substantial improvements in operating efficiency, comfort, and safety through a prolonged process of incremental improvement of these fundamental advances. Indeed, the first "breakthrough innovation" in aircraft, the Wright brothers' original powered glider, bears little or no resemblance to the commercial or military aircraft in regular use 75 years later. A long series of advances and improvements resulted in the complete transformation of the original "breakthrough" and laid the foundations for a large industry in both manufacturing and services.

Because of the fact that modern aircraft represent the integration of a components that themselves draw on numerous different technologies, the innovation process in commercial aircraft is fraught with uncertainty and risk. And the diversity of technologies and technical solutions to operating challenges also contribute to a relatively modest role for formal intellectual property protection mechanisms in the commercial aircraft industry. With the prominent exception of the Wright brothers' foundational patents, it is difficult to cite other instances of intellectual property rights having a significant exclusionary effect on competing firms within this industry in the United States or in other industrial economies.

The relative unimportance of formal intellectual property rights in the commercial aircraft industry also reflects the pervasive influence of government within the industry, most significantly as a supporter of R&D in military technologies that frequently has yielded results with important applications in commercial aircraft. Indeed, the U.S. industry's aircraft patent pool, the Manufacturers' Aircraft Association, was created at the behest of senior government officials during World War I in order to accelerate the development of the U.S. aircraft industry. The U.S. government has also been an important purchaser of military aircraft, a supporter of R&D with direct civilian applications, and a regulator of domestic air transportation for decades, creating incentives for adoption by commercial airlines of innovations from U.S. aircraft firms. Governments in other industrial economies similarly have exercised considerable influence through R&D funding, procurement, and regulation, and in other cases, direct control through state ownership, of both aircraft producers and commercial airlines.

In conclusion, it is arguable that in the absence of patents, the commercial aircraft industry of the late 20th century very likely would differ very little in its a structure and record of technical progress. Indeed, the U.S. aircraft industry operated in a "weak-patent" environment during 1917-75 as a result of the MAA. There can be little doubt, however, that had the influence of governments over the aircraft industries of the industrial economies somehow been eliminated, the current global industry structure and record of innovation would look very different indeed.

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Table 1: Annual and cumulative R&D investment, U.S. aircraft industry, 1945-82 (1972 dollars in millions)

year	NACA/NASA	Other federal civil aircraft R&D	Military R&D	Total federal R&D	Industry-financed R&D
1945	79.16	2.63	820.58	902.37	60.69
1946	84.28	2.28	952.16	1038.72	63.78
1947	60.61	2.02	705.05	767.68	74.75
1948	79.25	3.77	683.02	766.04	90.57
1949	100.95	3.81	788.57	893.33	133.33
1950	97.01	14.93	822.76	934.7	169.78
1951	108.58	19.27	1185.64	1313.49	287.22
1952	195.16	24.18	1884.28	2103.63	478.41
1953	129.25	40.82	2574.83	2744.9	576.53
1954	92.44	42.01	2793.28	2927.73	576.47
1955	77.3	46.06	2587.17	2710.53	526.32
1956	81.21	79.62	2562.1	2722.93	562.1
1957	77.04	123.27	2654.85	2855.16	604.01
1958	68.18	133.34	2780.3	2981.82	539.39
1959	71.01	153.84	2569.53	2794.38	501.48
1960	46.58	170.31	2196.51	2413.39	478.89
1961	56.28	164.5	2295.82	2516.59	441.56
1962	62.32	90.65	2286.12	2439.09	430.59
1963	92.05	108.79	2776.85	2977.68	326.36
1964	115.38	76.93	2663.46	2855.77	417.58
1965	137.1	68.55	2505.38	2711.02	474.46
1966	143.23	186.2	2621.09	2950.52	579.43
1967	169.41	284.45	2441.21	2895.07	714.29
1968	207.27	118.79	2429.09	2755.15	815.76
1969	248.85	149.77	2111.75	2510.37	701.61
1970	217.72	45.96	2410.96	2674.63	678.76
1971	218.75	76.04	2282.44	2577.23	536.1
1972	236	95	2429.6	2760.6	513.4
1973	296.12	70.96	2082.63	2449.71	419.73
1974	241.53	64.29	1800.81	2106.63	378.16
1975	249.6	58.83	1571.56	1879.99	306.81
1976	245.65	64.25	1779.5	2089.4	344.46
1977	270	66.43	1953.17	2289.6	376.83
1978	291.33	62.67	2338.99	2692.99	515.68
1979	317.63	55.69	1936.97	2310.29	624.23
1980	313.9	53.25	1933.35	2300.5	688
1981	268.92	54.19	2021.81	2344.92	733.81
1982	248.79	39.06	2102.72	2390.57	732.14
Total	6095.85	2917.35	77335.93	86349.14	17493.47
Share of total industry R&D (fed + industry-funded)	5.9	2.8	74.5	83.2	16.8

Table 2: US aircraft production, 1920-39 (# of units). SOURCE: Rae (1968)

year	civil	military
1920	72	256
1921	48	389
1922	37	226
1923	56	687
1924	60	317
1925	342	447
1926	654	532
1927	1374	621
1928	3127	1219
1929	5516	677
1930	2690	747
1931	1988	812
1932	803	593
1933	858	466
1934	1178	437
1935	1251	459
1936	1869	1141
1937	2824	949
1938	1823	1800
1939	3661	2195

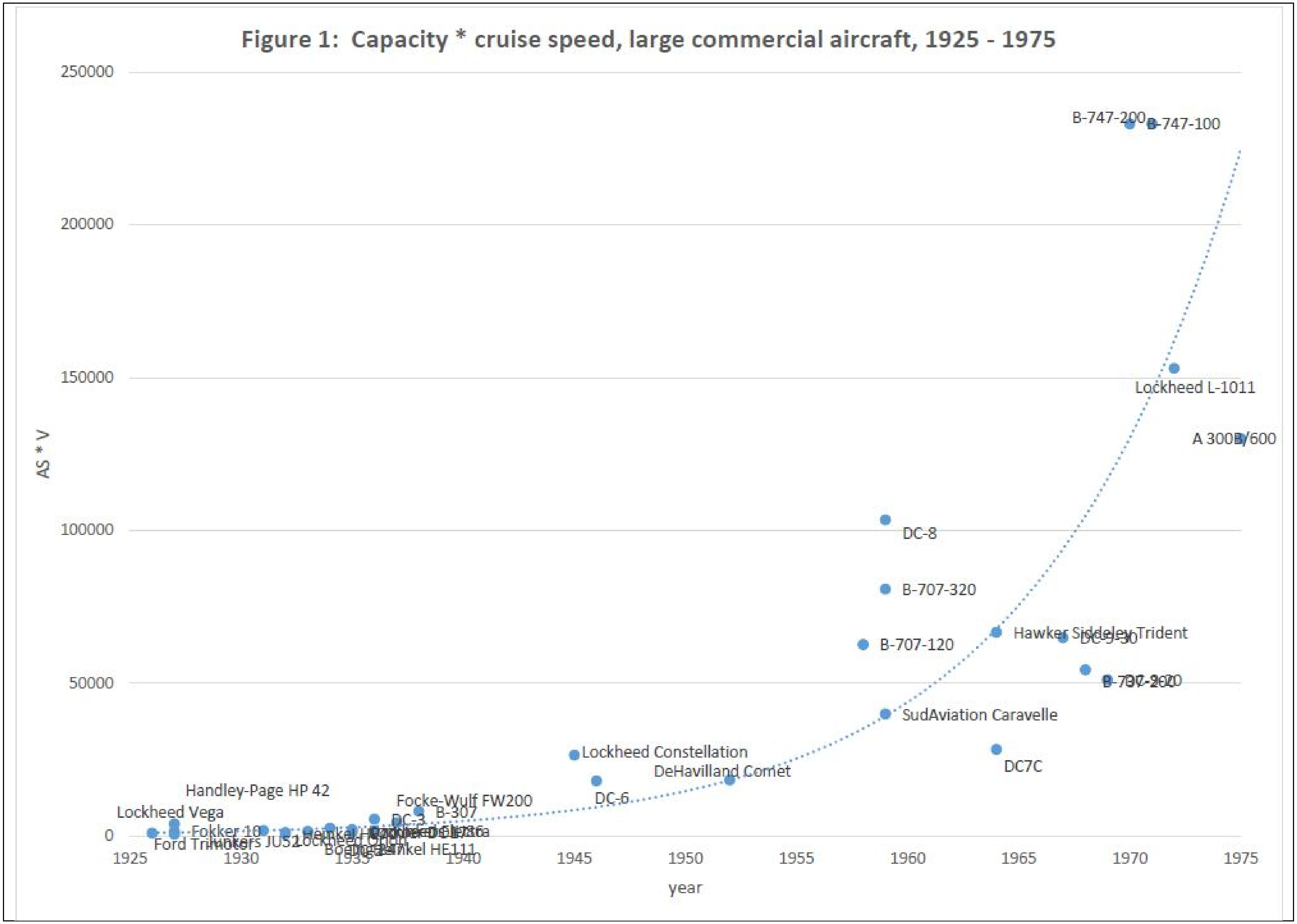


Figure 1: Capacity * cruise speed, large commercial aircraft, 1925 - 1975
AS * V
year
B-747-200
B-747-100
Lockheed L-1011
A 300B/600
DC-8
B-707-320
B-707-120
Hawker Siddeley Trident
DC-9-30
SudAviation Caravelle
DC7C
Lockheed Constellation
DeHavilland Comet
DC-6
Handley-Page HP 42
Lockheed Vega
Fokker 10
Ford Trimotor
Focke-Wulf FW200
B-307
DC-3
250000
200000
150000
100000
50000
0
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975

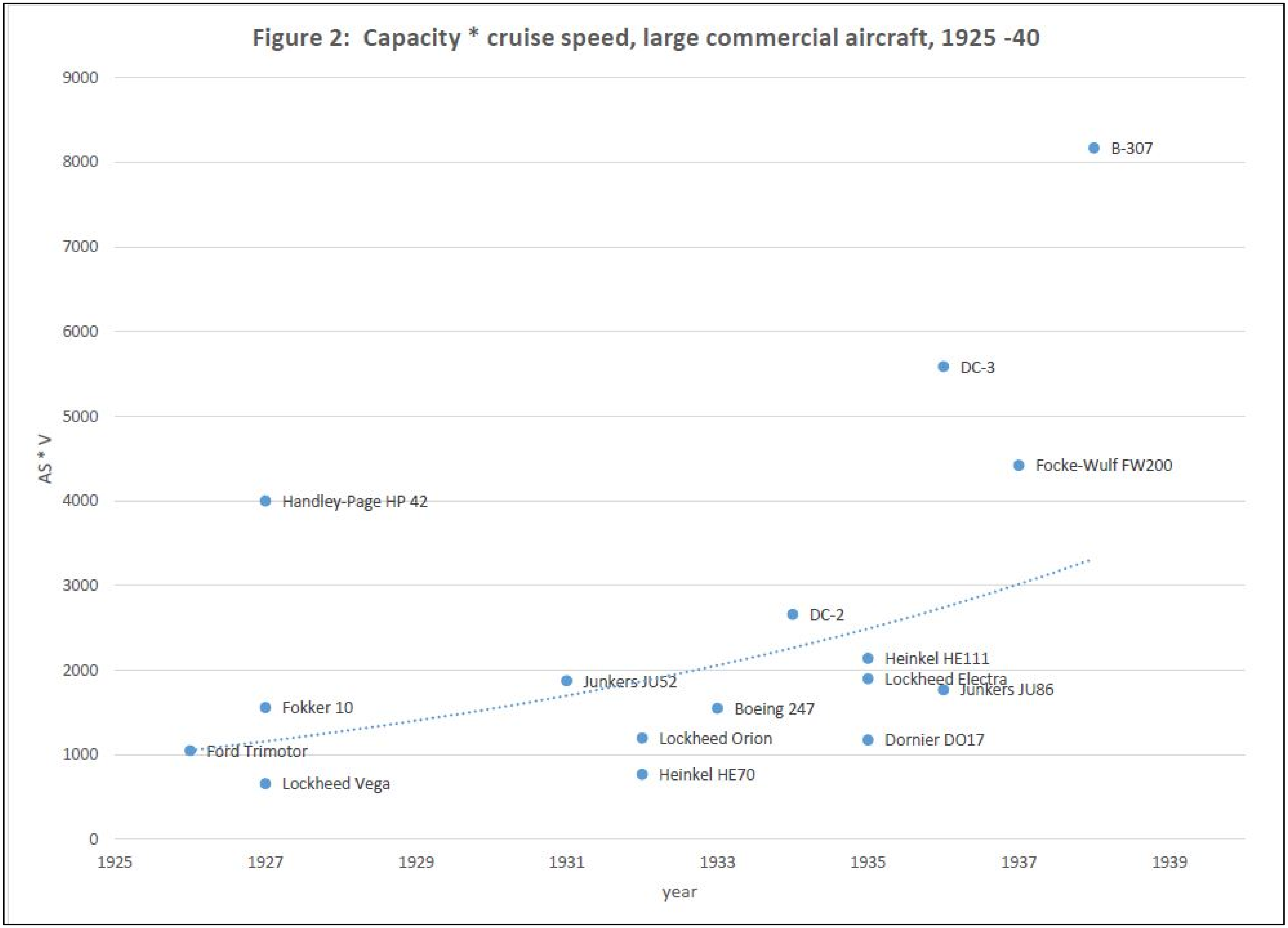


Figure 2: Capacity * cruise speed, large commercial aircraft, 1925 -40
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
AS * V
1925
1927
1929
1931
1933
1935
1937
1939
year
B-307
DC-3
Focke-Wulf FW200
Handley-Page HP 42
DC-2
Heinkel HE111
Lockheed Electra
Junkers JU86
Junkers JU52
Fokker 10
Boeing 247
Lockheed Orion
Dornier DO17
Ford Trimotor
Heinkel HE70
Lockheed Vega

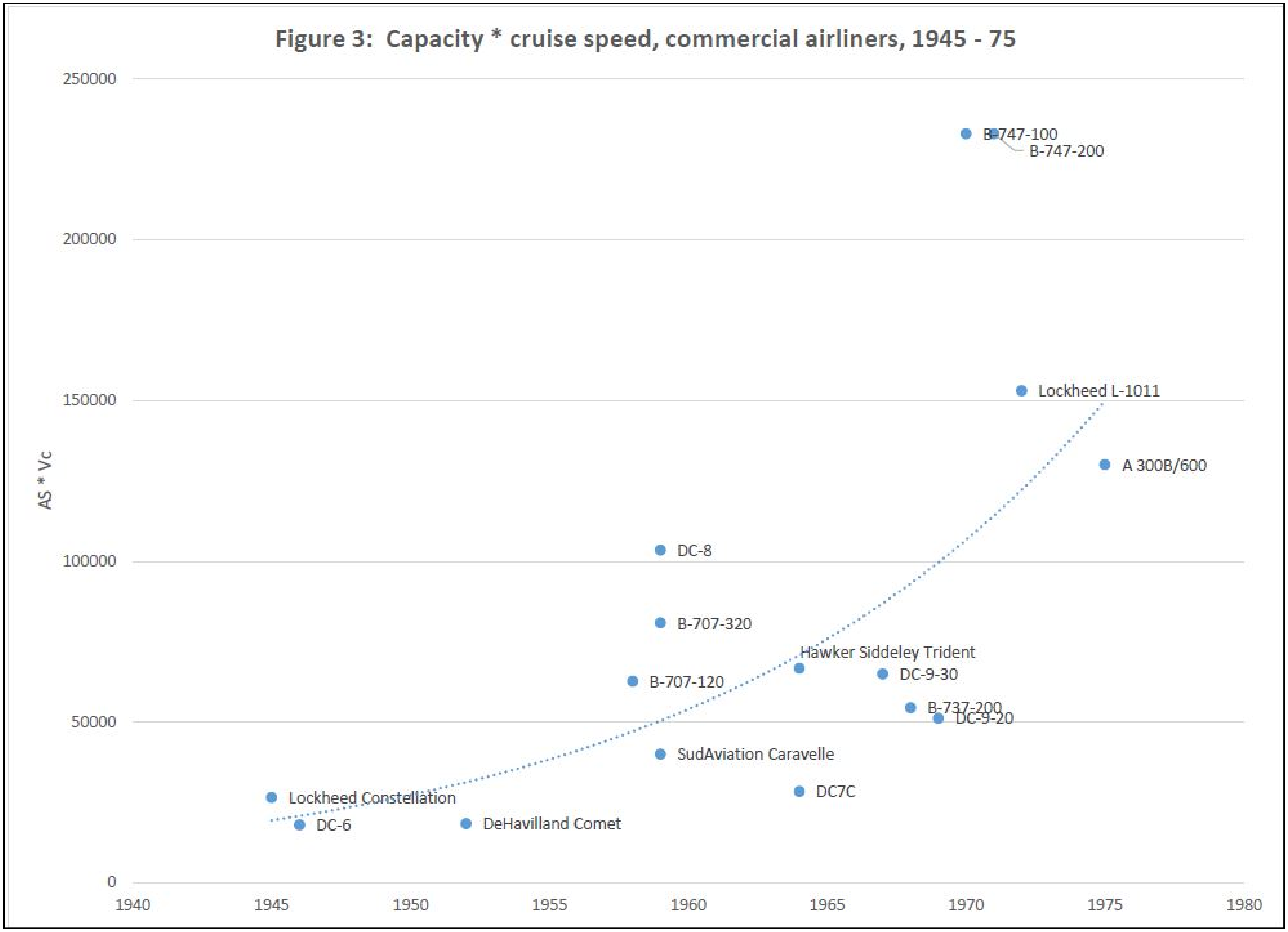


Figure 3: Capacity * cruise speed, commercial airliners, 1945 - 75
AS * Vc
250000
200000
150000
100000
50000
0
1940
1945
1950
1955
1960
1965
1970
1975
1980
B-747-100
B-747-200
Lockheed L-1011
A 300B/600
DC-8
B-707-320
Hawker Siddeley Trident
DC-9-30
B-707-120
B-737-200
DC-9-20
SudAviation Caravelle
DC7C
Lockheed Constellation
DC-6
DeHavilland Comet

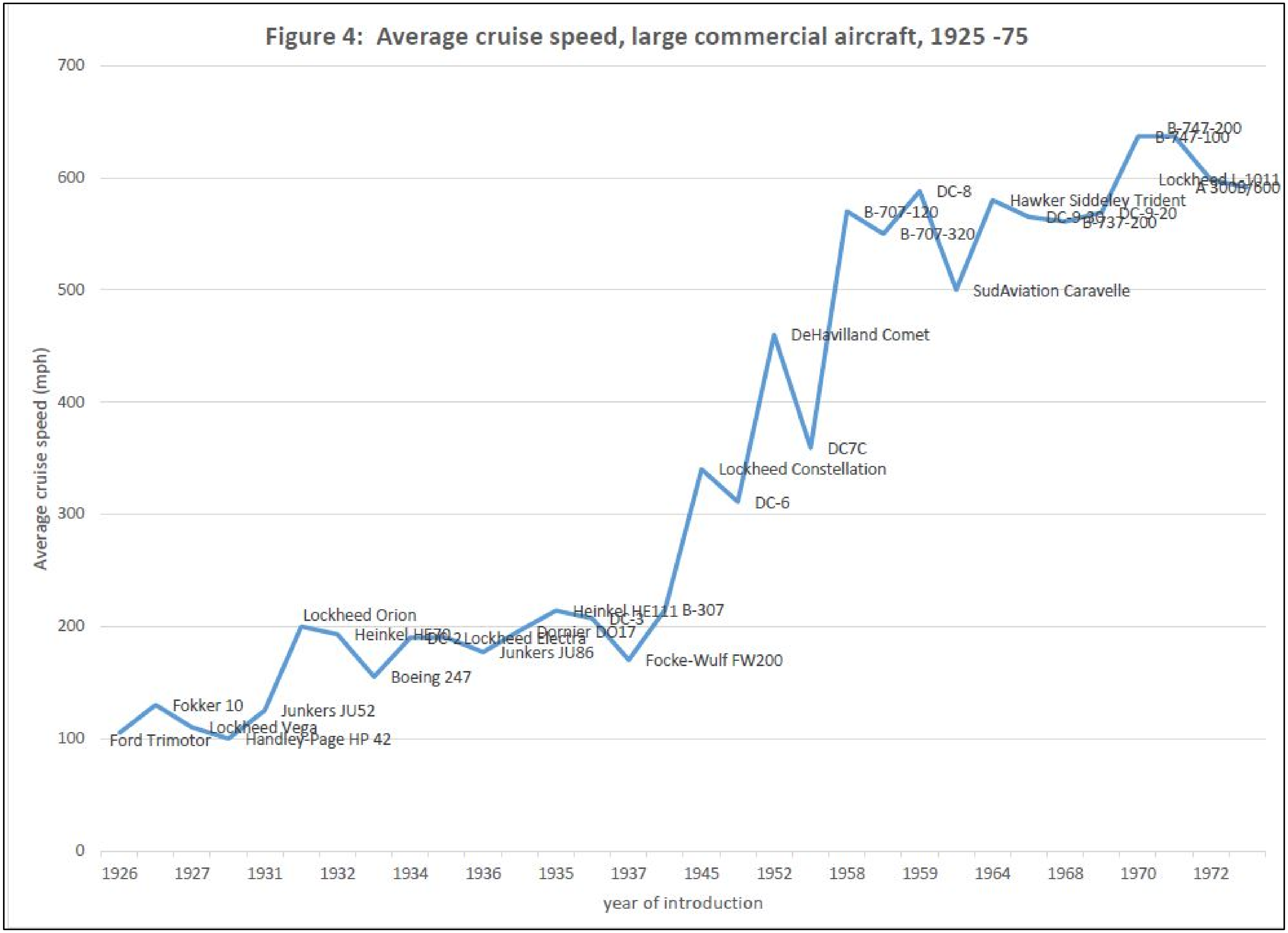


Figure 4: Average cruise speed, large commercial aircraft, 1925 -75
Average cruise speed (mph)
700
600
500
400
300
200
100
0
Ford Trimotor
Fokker 10
Lockheed Vega
Handley-Page HP 42
Junkers JU52
Lockheed Orion
Heinkel HE70
DC-2
Lockheed Electra
Boeing 247
Junkers JU86
Dornier DO17
Heinkel HE111
DC-3
B-307
Focke-Wulf FW200
Lockheed Constellation
DC-6
DeHavilland Comet
DC7C
B-707-120
B-707-320
DC-8
SudAviation Caravelle
Hawker Siddeley Trident
DC-9-30
B-737-200
DC-9-20
B-747-200
B-747-100
Lockheed L-1011
A 300B/600
1926
1927
1931
1932
1934
1936
1935
1937
1945
1952
1958
1959
1964
1968
1970
1972
year of introduction

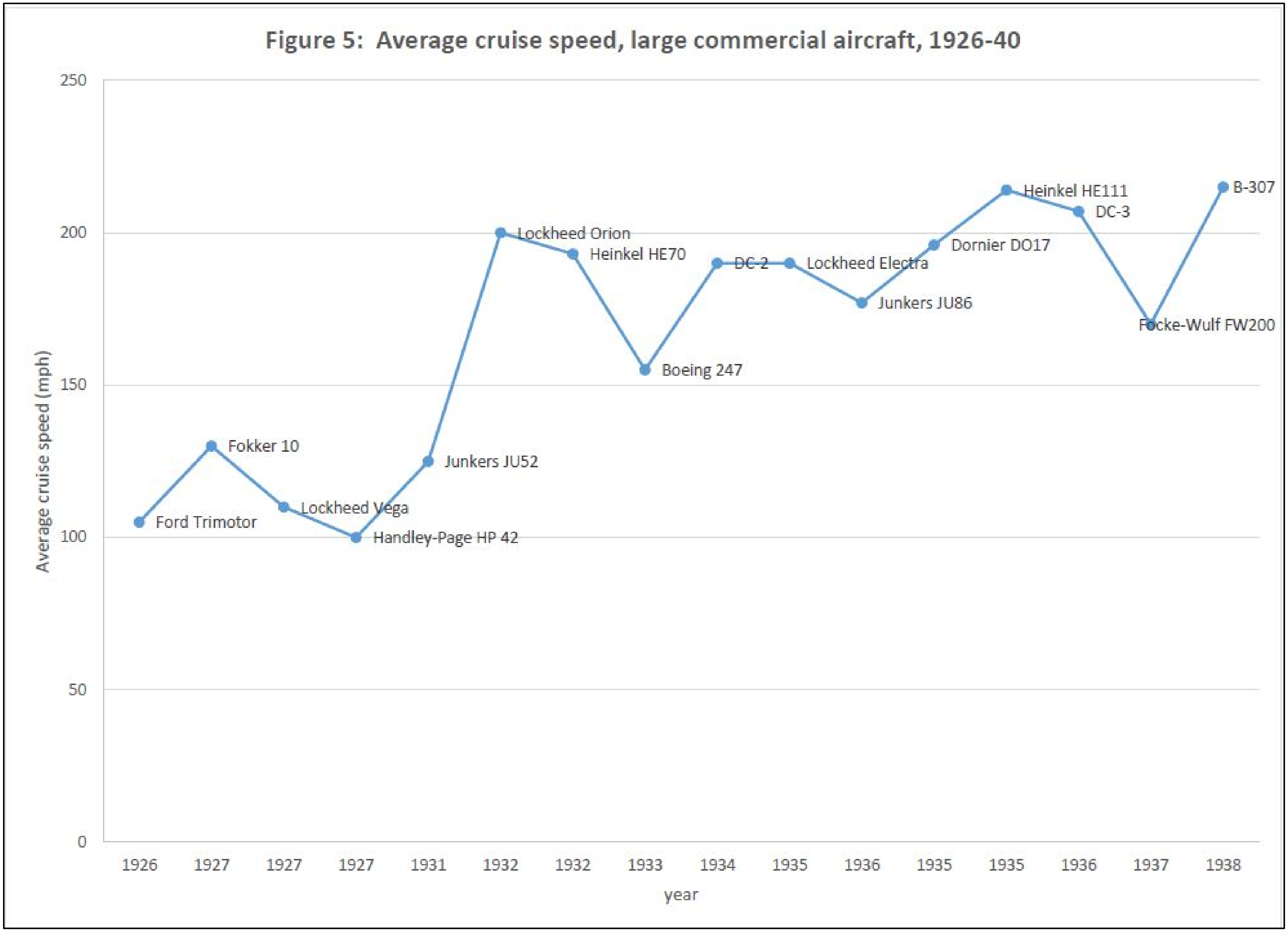


Figure 5: Average cruise speed, large commercial aircraft, 1926-40
Average cruise speed (mph)
250
200
150
100
50
0
Ford Trimotor
Fokker 10
Lockheed Vega
Handley-Page HP 42
Junkers JU52
Lockheed Orion
Heinkel HE70
Boeing 247
DC-2
Lockheed Electra
Junkers JU86
Dornier DO17
Heinkel HE111
DC-3
Focke-Wulf FW200
B-307
1926
1927
1927
1927
1931
1932
1932
1933
1934
1935
1936
1935
1935
1936
1937
1938
year


Figure 6: Average cruise speed, large commercial aircraft, 1945 - 75
Average cruise speed (mph)
0
100
200
300
400
500
600
700
Lockheed Constellation
DC-6
DeHavilland Comet
DC7C
B-707-120
B-707-320
DC-8
SudAviation Caravelle
Hawker Siddeley Trident
DC-9-30
B-737-200
DC-9-20
B-747-100
B-747-200
Lockheed L-1011
A 300B/600
1945
1946
1952
1953
1958
1959
1959
1959
1964
1967
1968
1969
1970
1971
1972
1975

Figure 7: Direct operating costs of multiengine U.S. commercial transports, first year of operation (1954$$)
SOURCE: Rosenberg et al., 1978, p. 65.

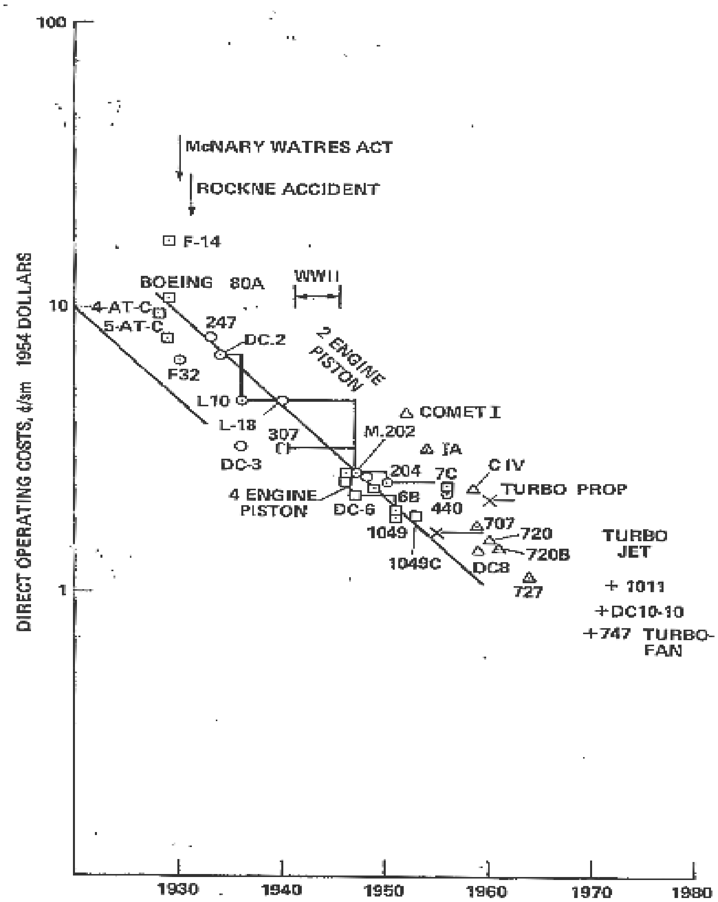
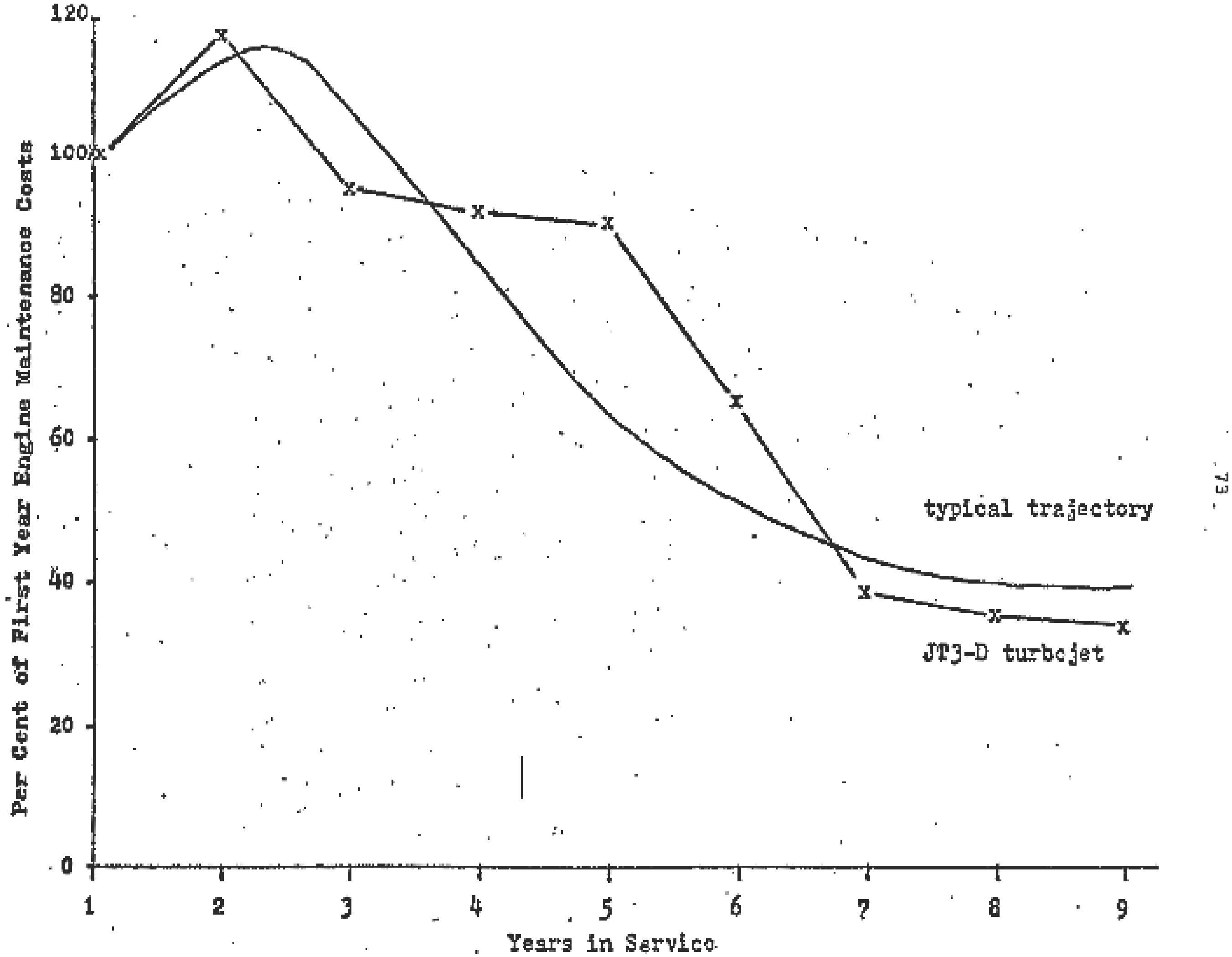


Figure 8: JT3D turbojet engine maintenance costs, service years 1 – 9
SOURCE: Rosenberg et al. (1978), p. 73



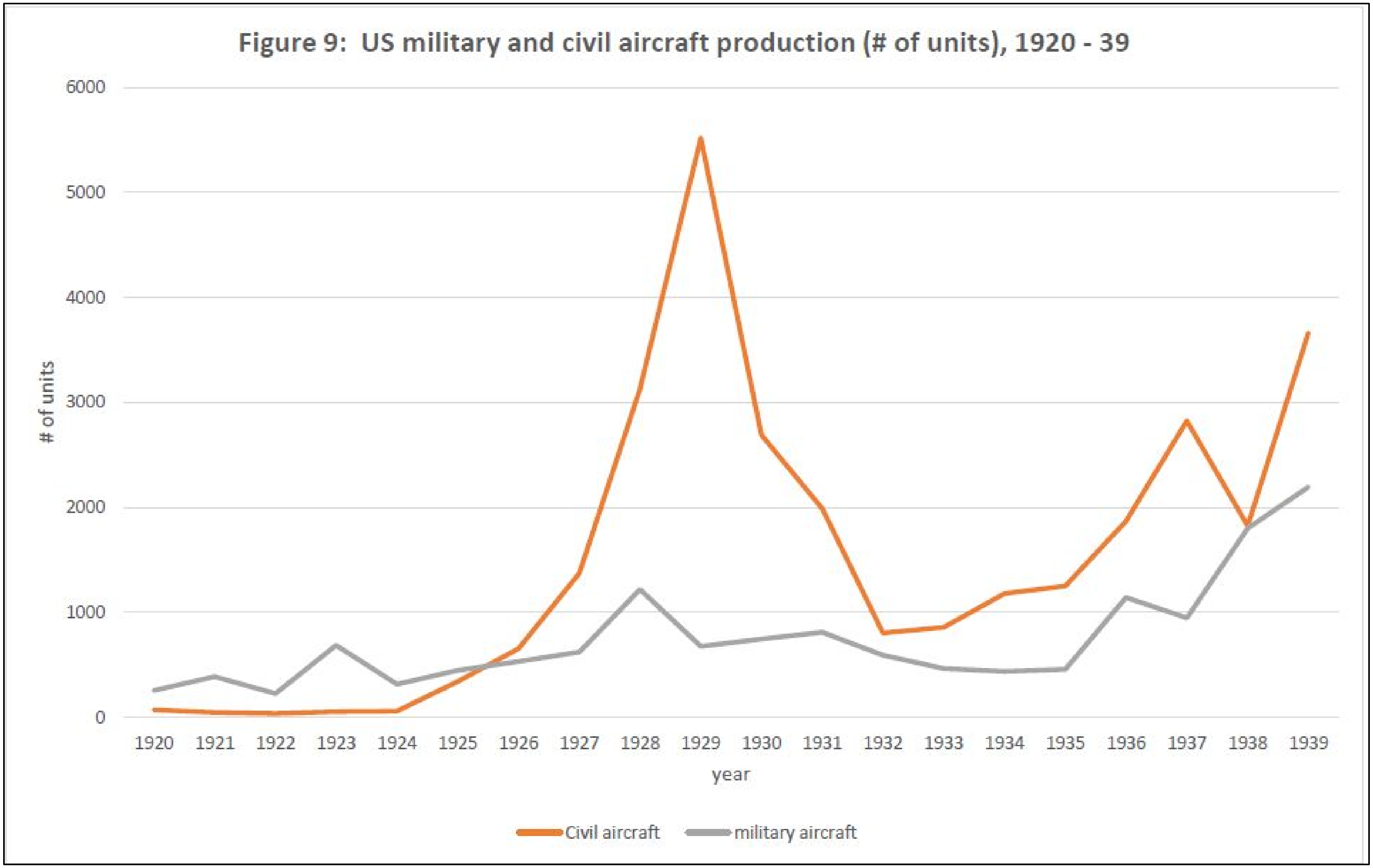


Figure 9: US military and civil aircraft production (# of units), 1920 - 39
6000
5000
4000
3000
2000
1000
0
# of units
1920 1921 1922 1923 1924 1925 1926 1927 1928 1929 1930 1931 1932 1933 1934 1935 1936 1937 1938 1939
year
Civil aircraft
military aircraft

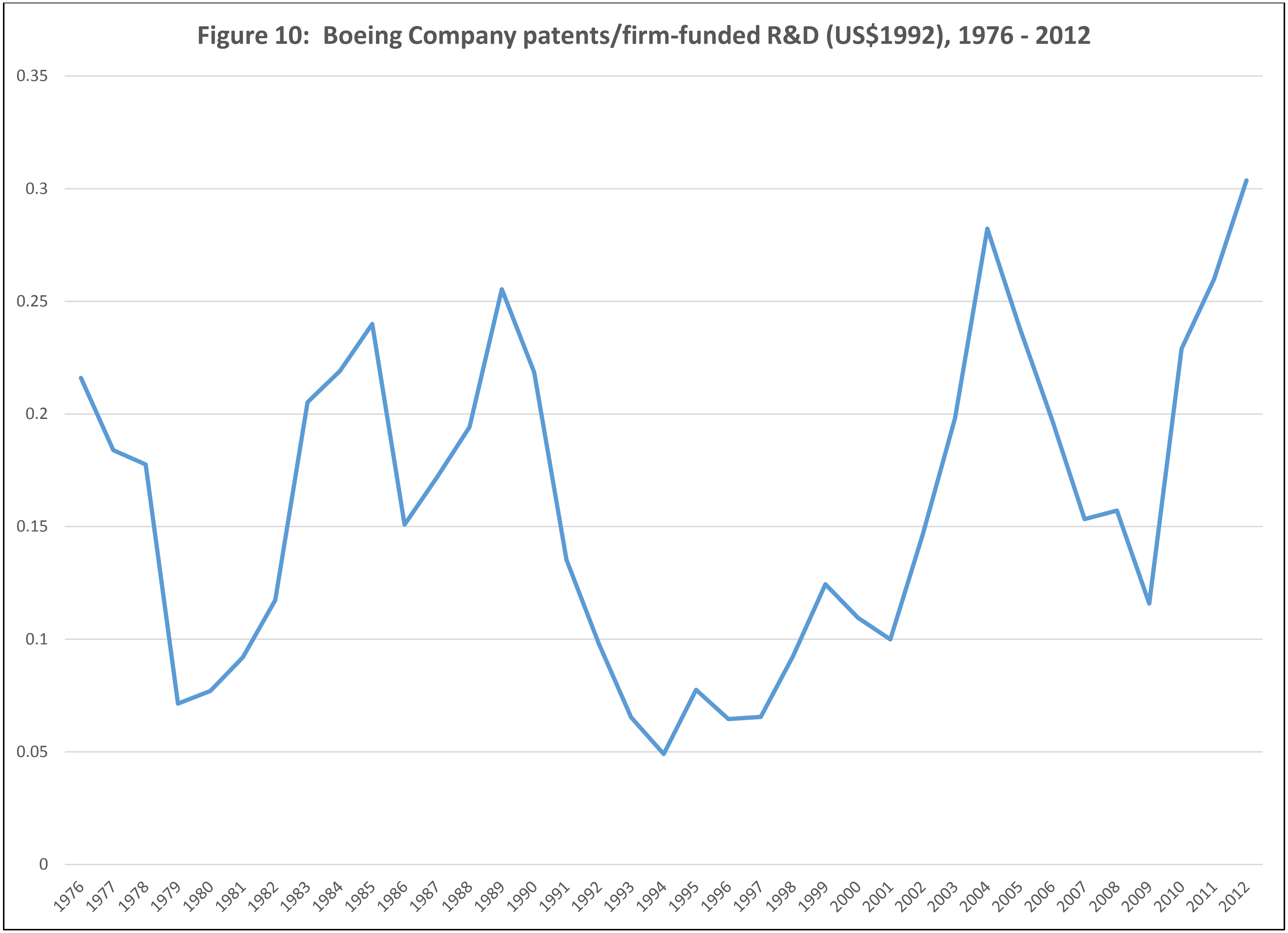


Figure 10: Boeing Company patents/firm-funded R&D (US$1992), 1976 - 2012
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

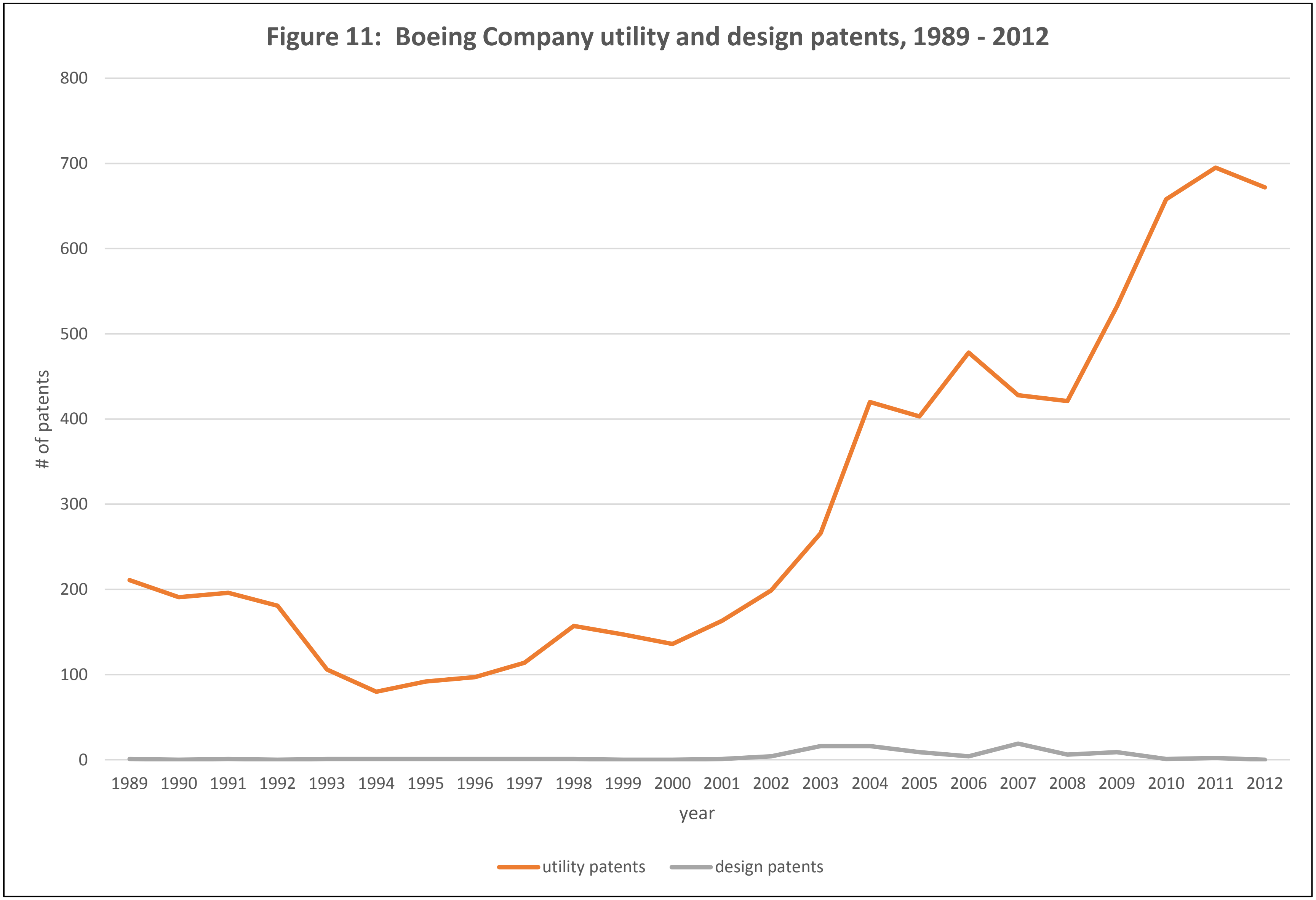


Figure 11: Boeing Company utility and design patents, 1989 - 2012
800
700
600
500
400
300
200
100
0
# of patents
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012
year
utility patents
design patents

Figure 12: U.S. aircraft patenting, 1900-96 (Roland, 2000, pp. 337-38)

Total aircraft patents (US patent class 244), 1900-1996

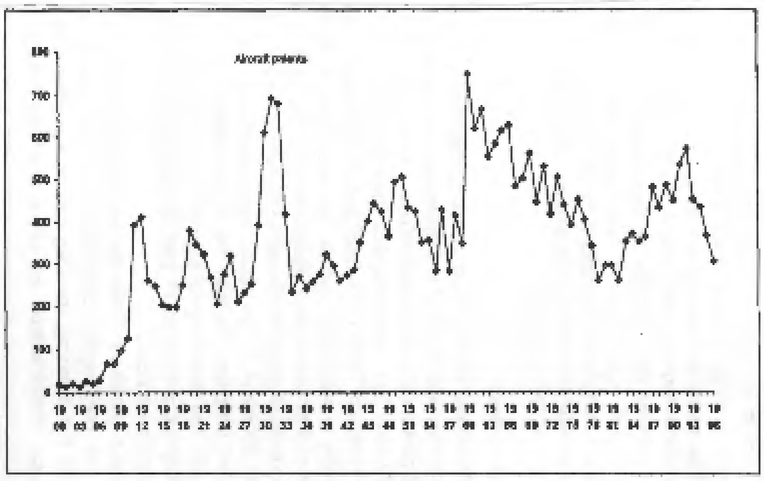


Figure 1. U.S. Department of Commerce, Patent and Trademark Office, USPAT file, at North Carolina State University. Aircraft Patents are Classification Number 244.

Aircraft patents as share of total U.S. patents, 1900-96

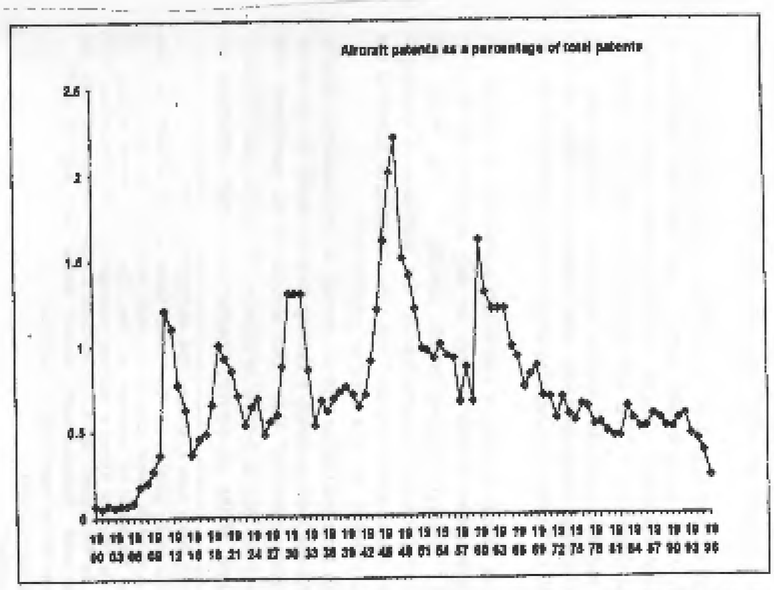


Figure 2. U.S. Department of Commerce, Patent and Trademark Office, USPAT file, at North Carolina State University. Aircraft Patents are Classification Number 244.

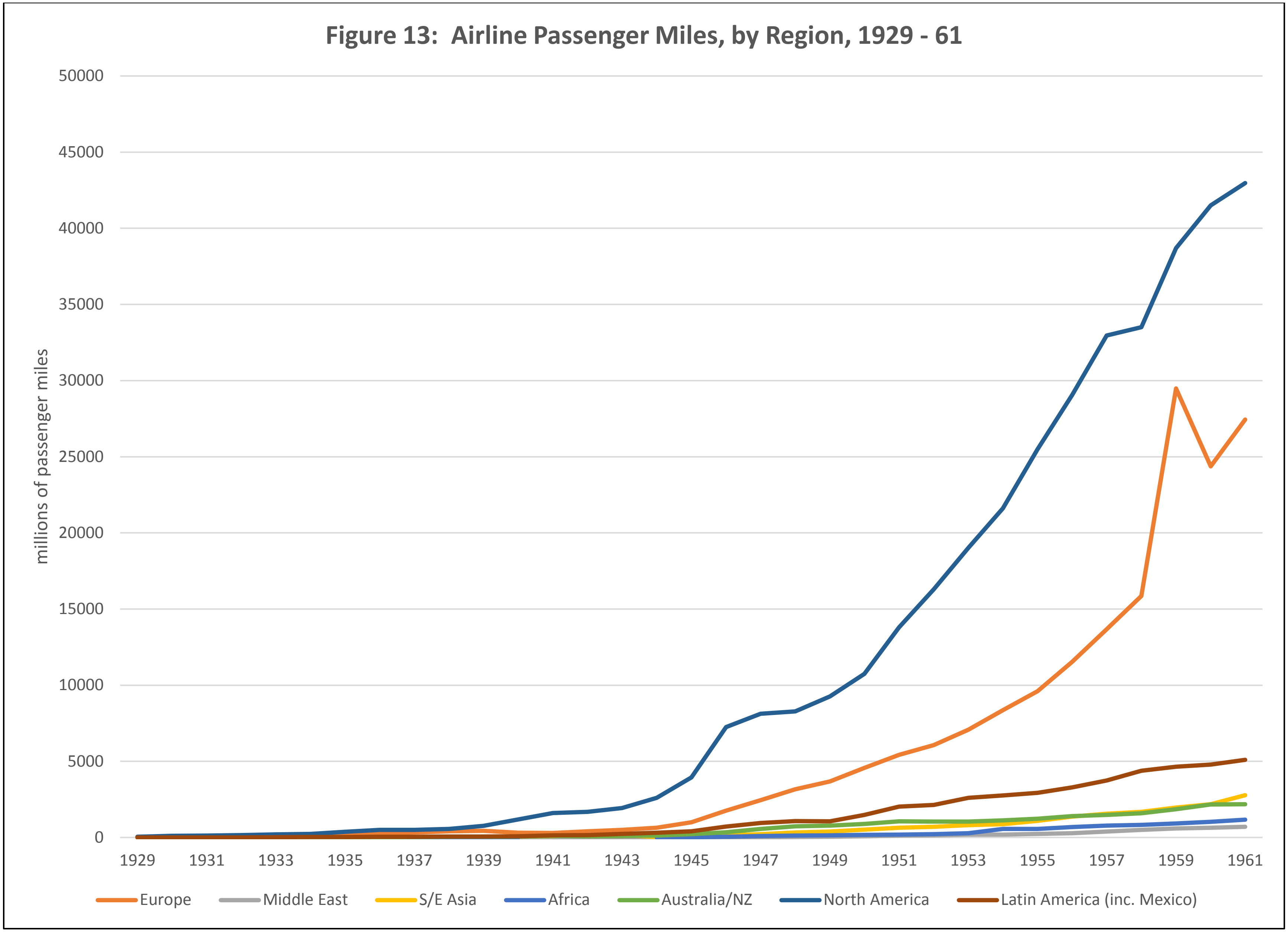


Figure 13: Airline Passenger Miles, by Region, 1929 - 61
millions of passenger miles
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
1929
1931
1933
1935
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
Europe
Middle East
S/E Asia
Africa
Australia/NZ
North America
Latin America (inc. Mexico)

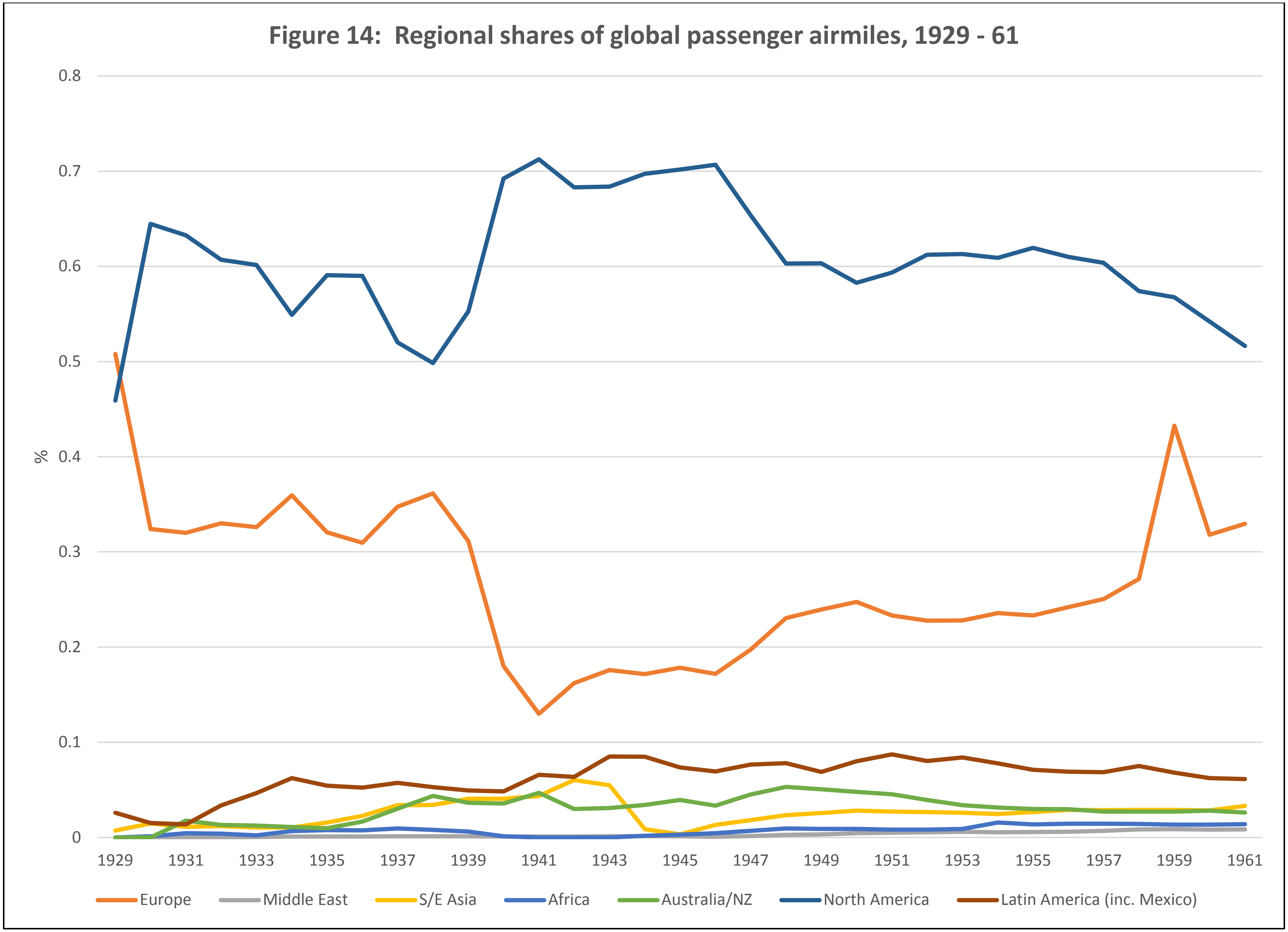


Figure 14: Regional shares of global passenger airmiles, 1929 - 61
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
%
1929
1931
1933
1935
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
Europe
Middle East
S/E Asia
Africa
Australia/NZ
North America
Latin America (inc. Mexico)

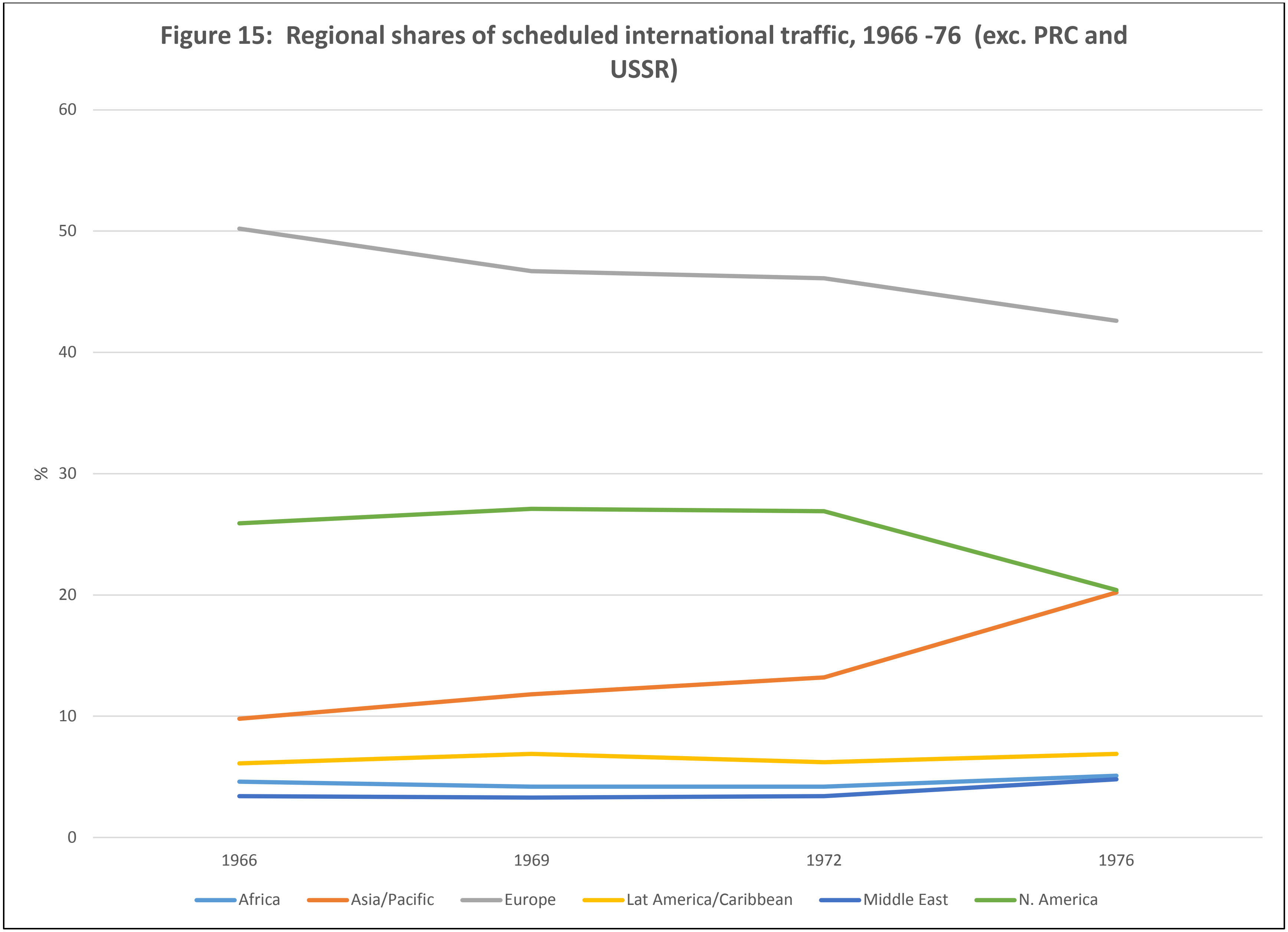


Figure 15: Regional shares of scheduled international traffic, 1966 -76 (exc. PRC and USSR)
60
50
40
30
20
10
0
%
1966
1969
1972
1976
Africa
Asia/Pacific
Europe
Lat America/Caribbean
Middle East
N. America

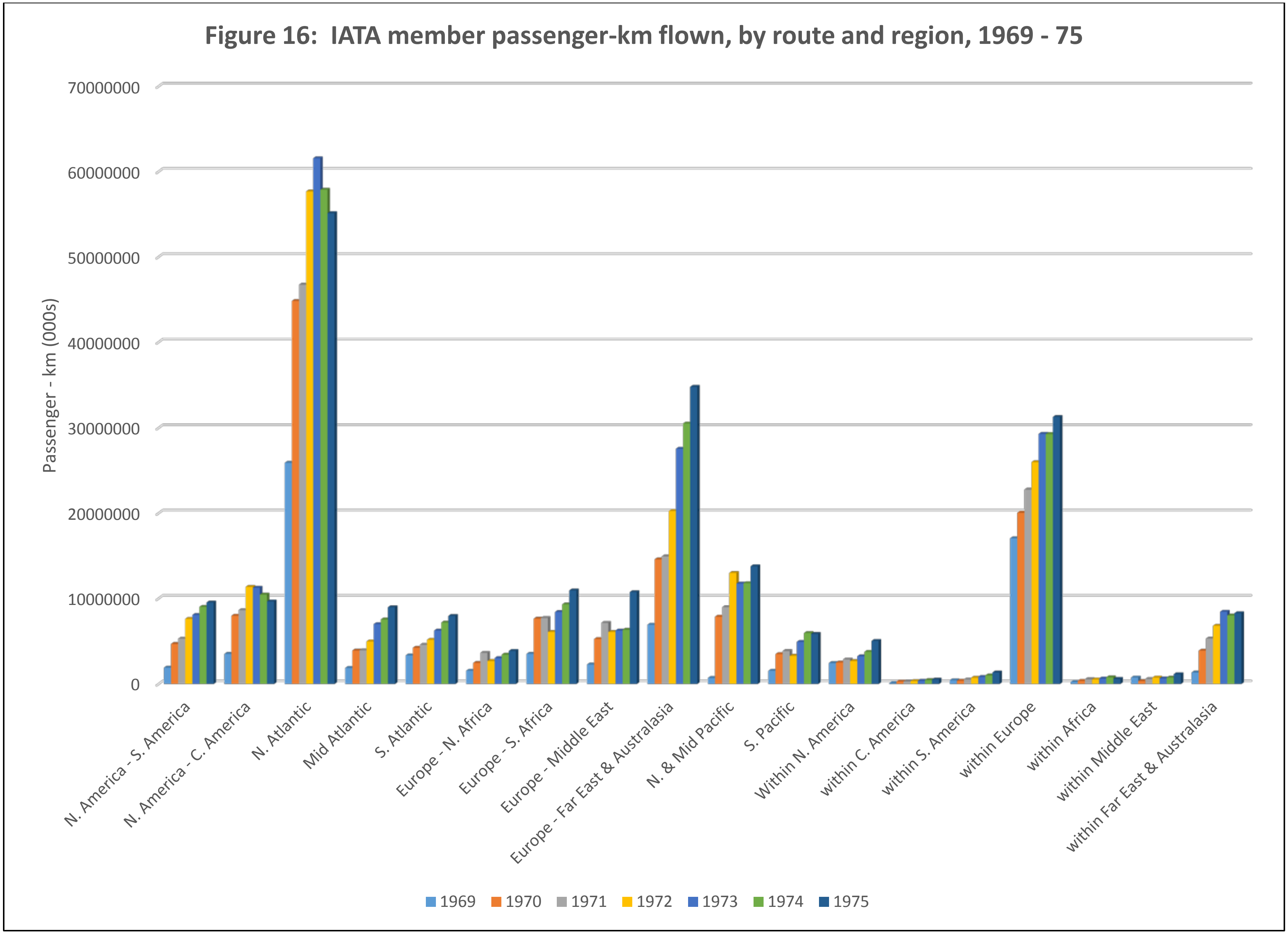


Figure 16: IATA member passenger-km flown, by route and region, 1969 - 75
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
Passenger - km (000s)
N. America - S. America
N. America - C. America
N. Atlantic
Mid Atlantic
S. Atlantic
Europe - N. Africa
Europe - S. Africa
Europe - Middle East
Europe - Far East & Australasia
N. & Mid Pacific
S. Pacific
Within N. America
within C. America
within S. America
within Europe
within Africa
within Middle East
within Far East & Australasia
1969
1970
1971
1972
1973
1974
1975

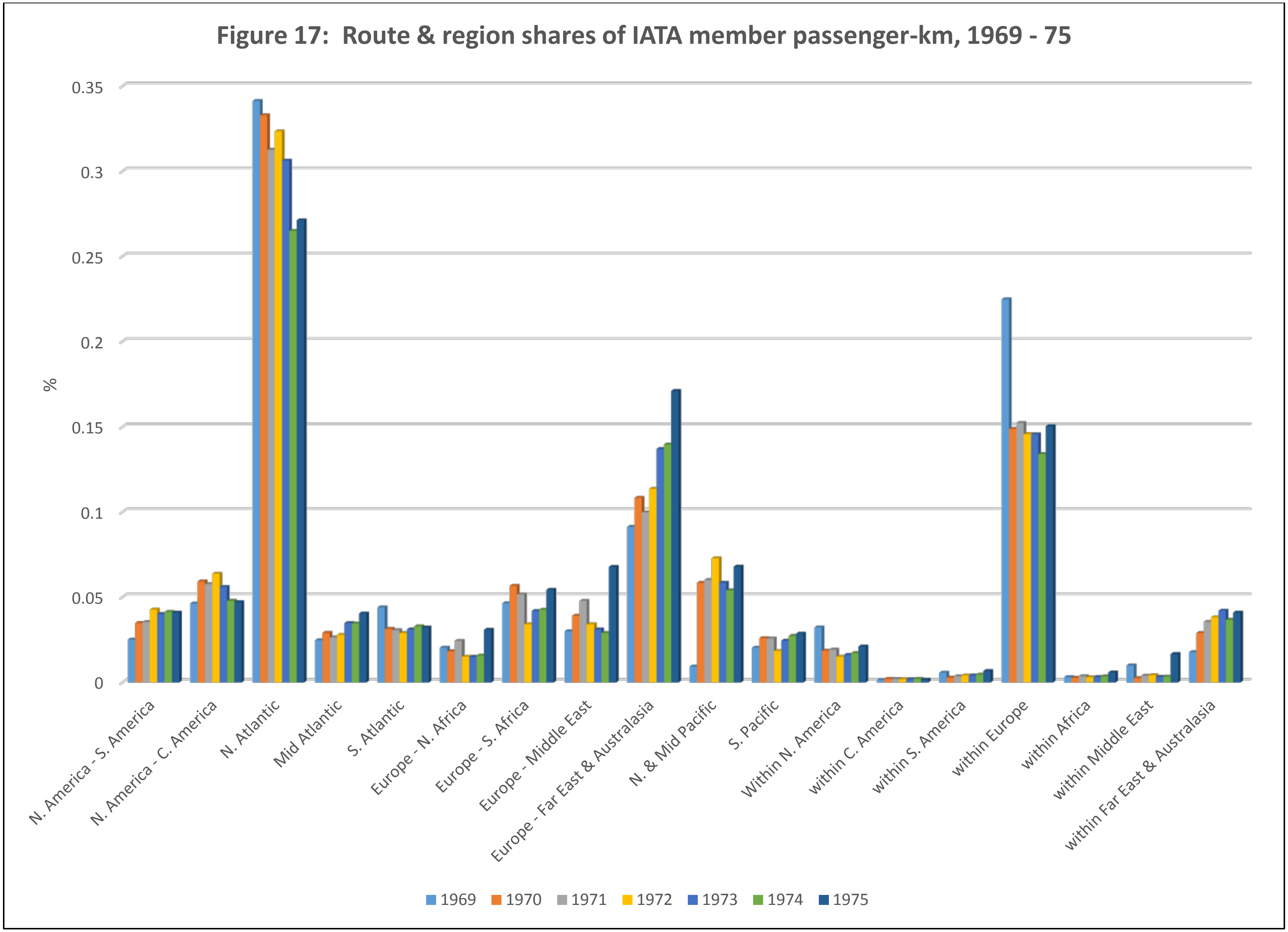


Figure 17: Route & region shares of IATA member passenger-km, 1969 - 75
%
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
N. America - S. America
N. America - C. America
N. Atlantic
Mid Atlantic
S. Atlantic
Europe - N. Africa
Europe - S. Africa
Europe - Middle East
Europe - Far East & Australasia
N. & Mid Pacific
S. Pacific
Within N. America
within C. America
within S. America
within Europe
within Africa
within Middle East
within Far East & Australasia
1969
1970
1971
1972
1973
1974
1975

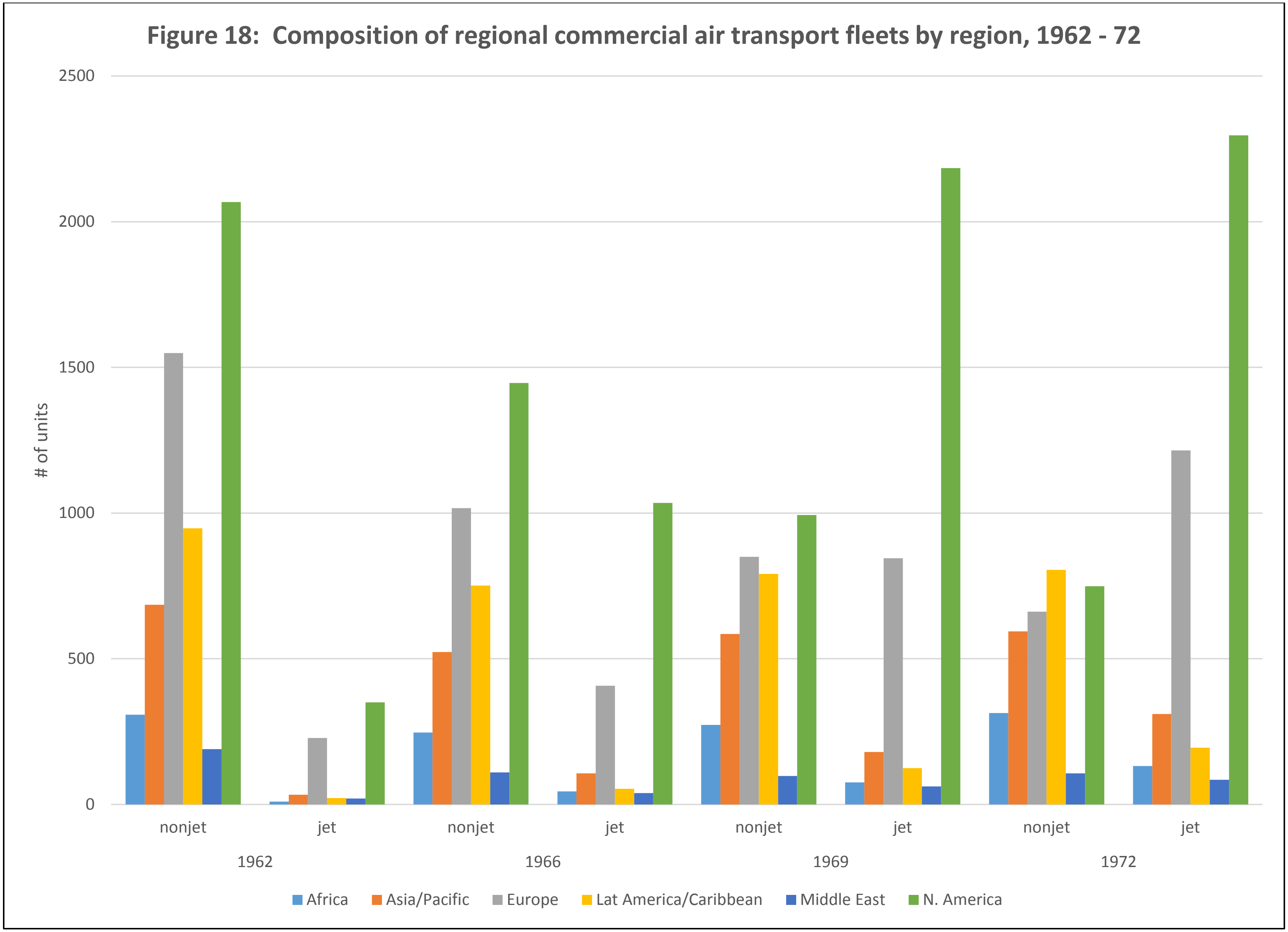


Figure 18: Composition of regional commercial air transport fleets by region, 1962 - 72
# of units
2500
2000
1500
1000
500
0
nonjet
jet
nonjet
jet
nonjet
jet
nonjet
jet
1962
1966
1969
1972
Africa
Asia/Pacific
Europe
Lat America/Caribbean
Middle East
N. America

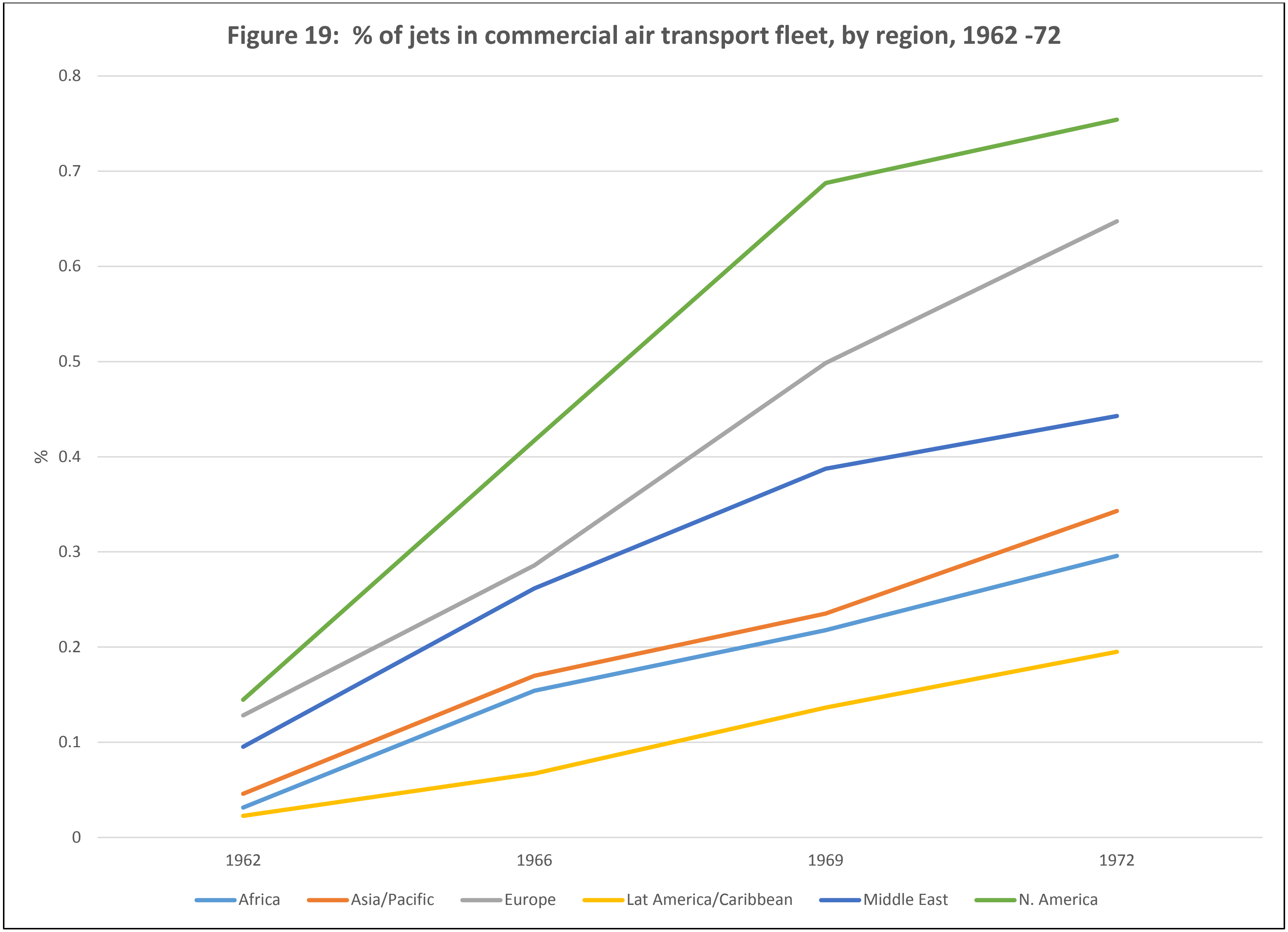


Figure 19: % of jets in commercial air transport fleet, by region, 1962 -72
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
%
1962
1966
1969
1972
Africa
Asia/Pacific
Europe
Lat America/Caribbean
Middle East
N. America

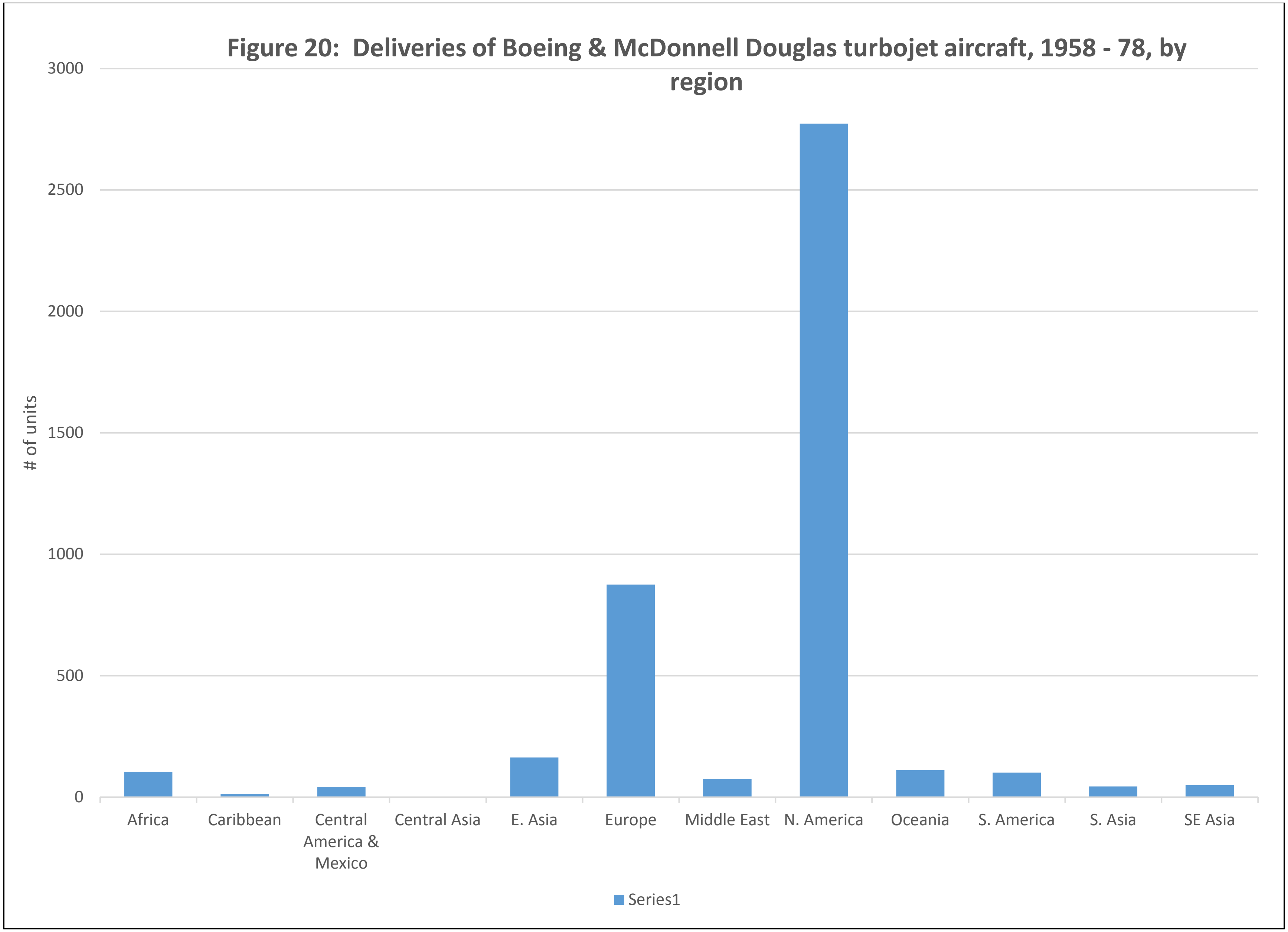
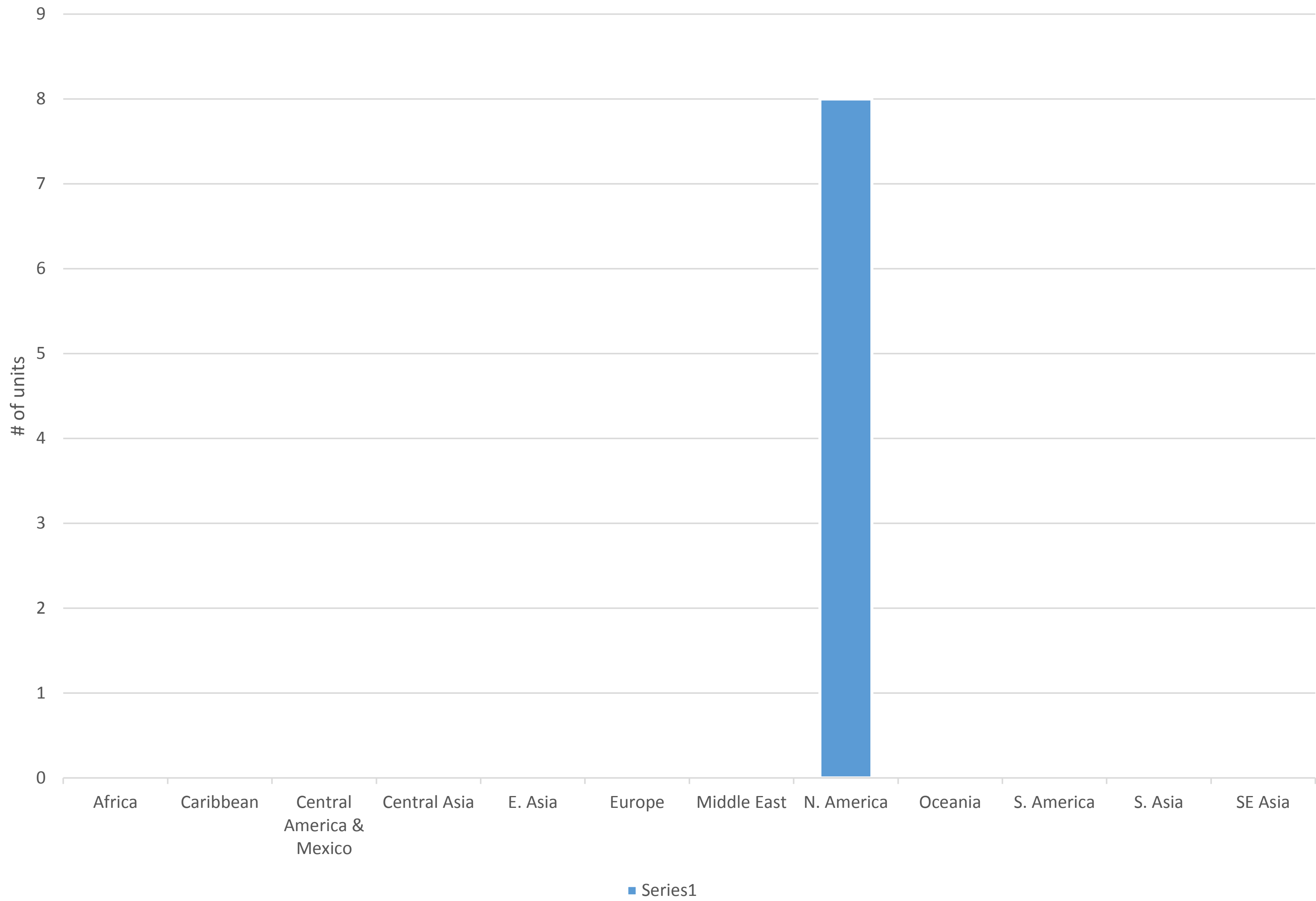


Figure 20: Deliveries of Boeing & McDonnell Douglas turbojet aircraft, 1958 - 78, by region
# of units
3000
2500
2000
1500
1000
500
0
Africa
Caribbean
Central America & Mexico
Central Asia
E. Asia
Europe
Middle East
N. America
Oceania
S. America
S. Asia
SE Asia
Series1

Figure 21: Deliveries of Boeing and McDonnell Douglas turbojet aircraft by region, 1958



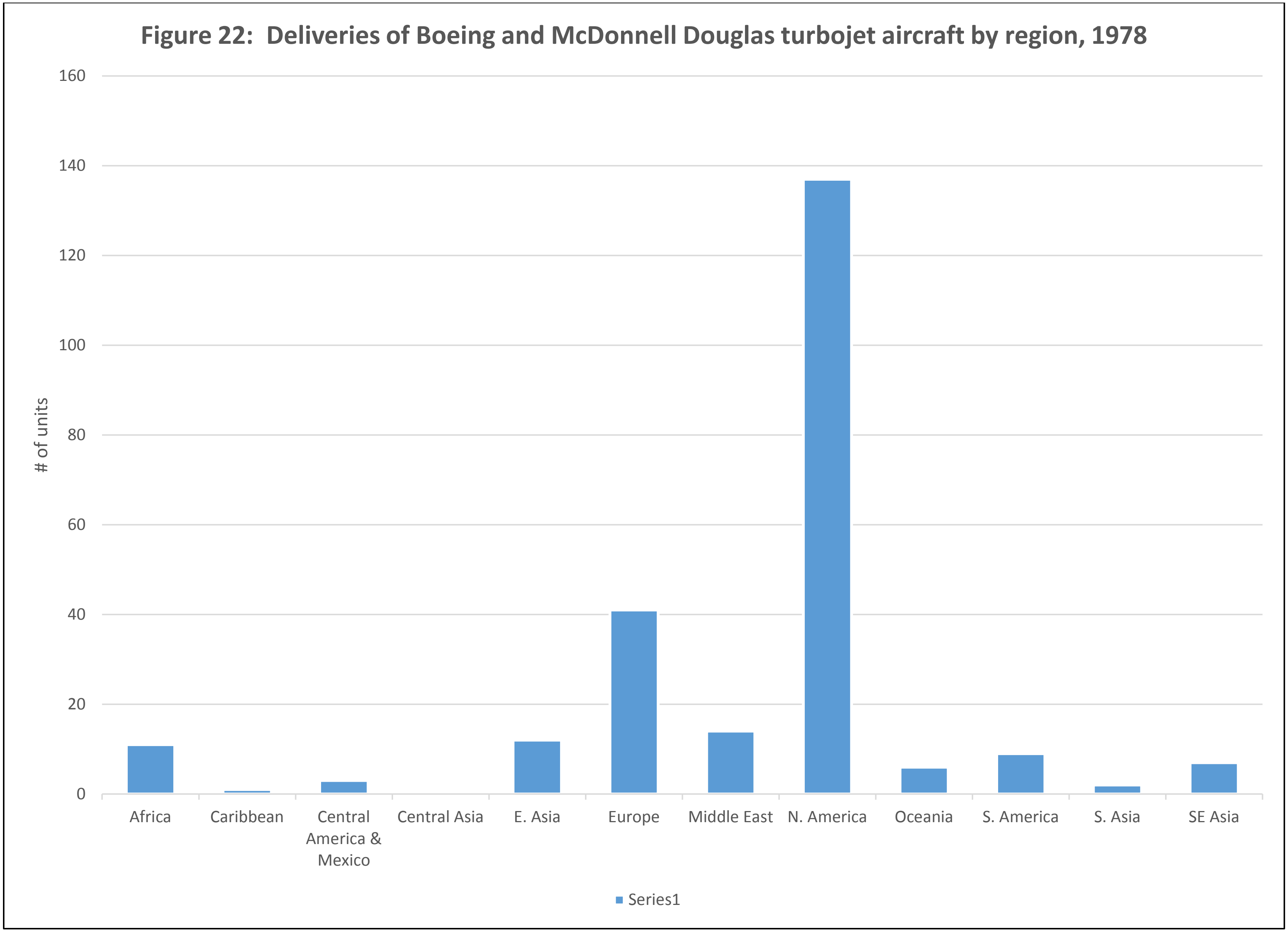


Figure 22: Deliveries of Boeing and McDonnell Douglas turbojet aircraft by region, 1978
# of units
160
140
120
100
80
60
40
20
0
Africa
Caribbean
Central America & Mexico
Central Asia
E. Asia
Europe
Middle East
N. America
Oceania
S. America
S. Asia
SE Asia
Series1