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Introduction

1.1 Definitions of Performance

The word *performance* has been defined many times—the following two definitions, provided in dictionaries of general word usage, encapsulate much of what is discussed in this book:

- (1) Performance describes the “capabilities of a machine or product [in this case, an airplane], especially when observed under particular conditions” [1].
- (2) Performance is the “manner in which or the efficiency with which something [in this case, an airplane] reacts or fulfills its intended purpose” [2].

The first definition highlights the *capabilities* of the product. Identifiable attributes of interest that quantify the capabilities of any airplane include the payload that can be carried over a defined distance, the airplane's stall speeds, rates of climb, turn radii, optimum cruise speeds and altitudes, takeoff and landing distances, and so forth. These are all performance attributes that, for a particular set of conditions, can be established by calculation or measurement.

When describing an airplane's performance, the associated conditions under which these attributes were determined is critical information—without which, the data would be meaningless. Frequently, it is the combination of the airplane's weight, the altitude at which it flies, and the ambient air temperature that must be established to describe adequately such performance capabilities. This set of conditions occurs so often in performance discussions, it has its own abbreviation: WAT (for weight, altitude, and temperature). The significance of this combination will become apparent in the ensuing discussions. The barometric pressure of the ambient air around an airplane is a function of altitude, and, through a fundamental law of gas dynamics, air density is linked to pressure and temperature. Consequently, this combination of altitude and air temperature can be seen to influence significantly the performance of an airplane by affecting the engines' thrust and the aerodynamic forces that are generated by the relative motion of the airplane with respect to the surrounding air. An airplane departing from Denver International Airport, Colorado (elevation 5434 ft) on a hot summer day requires a substantially longer takeoff distance compared to that which would be required at Shannon Airport, Ireland (elevation 46 ft) in mid-winter for a similar takeoff weight, for example.

A complete and accurate description of the operating environment is essential when fully describing the capabilities of an airplane, and this goes beyond the WAT conditions. The type of runway surface—for example, textured or smooth—affects braking distances. The presence of standing water or snow on the runway reduces an airplane's acceleration during takeoff, increasing the required takeoff distance. Winds too impact an airplane's performance. Trip times and fuel usage can be significantly affected by jet streams, which are fast flowing, narrow air currents found in the atmosphere at altitudes of about 30 000 to 40 000 ft. Takeoff and landing distances

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are shortened when operating into a headwind, compared to a nil wind condition. The presence of turbulence is a consideration when a pilot selects an approach speed for landing, and, consequently, this can influence an airplane's landing distance.

The performance capabilities of an airplane naturally depend on the thrust produced by the engines. The thrust of jet engines is not unlimited—it is restricted, or governed, at certain critical flight conditions (e.g., during takeoff) based on such factors as the ambient air temperature, altitude, and airplane speed. The engine's electronic control system governs the engine to ensure that its structural integrity is not compromised when producing the defined, or rated, thrust.

All airplane systems have an indirect impact on an airplane's performance by virtue of their installed weight, which makes up part of the airplane's operating empty weight (OEW). Several systems, however, can also have a direct impact on performance—for example, the cabin pressurization and air conditioning systems extract power from the engines (either as electrical power or as compressed air) at the expense of the available propulsive power. Consequently, the rate of climb for certain airplane types, under demanding conditions, can depend on the air conditioning settings selected by the pilot.

An airplane's performance also depends on its configuration, which, in this context, describes the position or setting of re-configurable parts of the airplane by the flight crew or flight control system—that is, the positions of the flight controls (e.g., flaps, slats, rudder, and ailerons) and undercarriage, and so forth. One important consequence—which all student pilots learn at an early stage of their training—is that an airplane does not have a single stall speed, but rather a range of stall speeds depending on its configuration and the associated WAT values. Interestingly, stall speeds also depend on the pilot's actions prior to the stall (e.g., the airplane's bank angle and the rate at which the airspeed decreases are factors that can influence a stall, albeit to a lesser extent than WAT).

The second general definition of performance, given earlier, extends these ideas by indicating that it is the manner in which, or the efficiency with which, the airplane accomplishes these actions that is a measure of its performance. In other words, performance topics also address the question of how well an airplane accomplishes its task or mission. A definition of performance provided by the United States Federal Aviation Authority is that it is “a measure of the accuracy with which an aircraft, a system, or an element of a system operates compared against specified parameters” [3]. This expands the discussion of performance to the determination of parameters that facilitate comparative assessments of airplane performance to be conducted. An important comparative measure of an airplane's overall performance is its payload–range capability. The standard presentation of this information is a chart that indicates, on one axis, the payload (i.e., the mass or weight of the passengers, baggage, and freight) plotted against, on the other axis, the distance that can be flown for a given set of mission rules (which defines the flight profile and fuel reserves). *Efficiency* is all about achieving the desired result—for example, flying a set distance with a given payload—with the least effort expended or resources consumed. The determination of the optimum conditions, in terms of flight speeds and cruise altitudes, that will minimize the trip fuel or, alternatively, the trip cost are classic airplane performance studies. An extension of studies of this type considers the environmental impact of the flight in terms of the noise generated or the exhaust emissions produced.

Another important attribute that often gets considered under the topic of performance is the manner in which the airplane responds or reacts to control inputs by the pilot (or flight control system) or to external influences such as atmospheric turbulence. The response of the airplane to a sudden vertical gust depends on the airplane's speed and its aerodynamic characteristics (e.g., the lift-curve slope and the wing loading), for example.

The study of the response of an airplane to a set of applied forces (e.g., lift, weight, drag, engine thrust) is known as *flight mechanics*, which is fundamentally based on the application

of Newtonian mechanics. The subject of flight mechanics has traditionally covered two separate, but related, topics: airplane performance (which primarily deals with trajectory analysis) and airplane stability and control. This book addresses the former topic, as applied to jet transport airplanes. All elements of a typical flight are considered (i.e., takeoff, climb, cruise, descent, maneuver, approach, and land). For a performance assessment of an airplane to have real value, however, the context and the operating environment need to be clearly defined and understood. For commercial jet transport airplanes, this context is to a large extent imposed by operational and regulatory procedures and constraints. Many of these considerations have traditionally not been addressed in academic textbooks on the subject of airplane performance, but are well known, of course, to those closely involved with the planning and execution of flight operations. In this book, performance discussions have extended many of the traditional, idealized performance representations to include key operational and regulatory aspects. The determination of the maximum takeoff weight that a pilot can safely utilize for a given set of conditions, for example, can be a complex study with many considerations, which include the runway length, slope, and surface condition; the wind and ambient conditions (viz., air temperature and barometric pressure); location of obstacles near to the intended flight path; airplane configuration (e.g., flap setting); and airplane limitations (e.g., brake energy limits, which are important in the event of a rejected takeoff).

Another point that arises from the above-mentioned definitions of performance is that the most important performance characteristics of any product are those that relate most closely to the primary purpose or role of the product. In broad terms, the role of commercial transport airplanes is to transport people and goods efficiently and safely, by air, from one geographical location to another within an aviation infrastructure (comprising airports and related services, air traffic control, ground and satellite navigation systems, and so forth).

1.2 Commercial Air Transportation

Commercial air travel is considered to have started on January 1, 1914, when Tony Jannus—flying a biplane designed to take off and land on water—transported the first recorded fee-paying passenger (across Tampa Bay in Florida, United States) [4]. One hundred years later—a time period that is associated with aviation advancements on a previously unimaginable level—saw 8.6 million passengers transported each day on commercial flights around the world [5]. Nearly 1400 airlines serviced 3800 airports [5]. Passenger and cargo air transportation had grown to become an essential part of modern life and a vital component of global economic activity. In 2014, about 35% of world trade by value was transported by airfreight [5].

Commercial air travel continues to grow. Air traffic—measured in terms of revenue passenger kilometers (RPK)—has experienced global long-term growth rates of approximately 5% per year. Informed forecasts by key stakeholders predict average growth rates of 4.5–5% per year for the forecast period (i.e., until 2035) [6, 7]. In 2015, the number of in-service jet transport airplanes, including freighter aircraft, was 22 510 (made up as follows: widebody types 22.4%, single-aisle types 66.0%, and regional jets 11.6% [7]); to satisfy increasing passenger demand, the global fleet will need to double by about 2035 [7, 8]. As might be expected, air traffic growth is linked to economic growth—both at a regional and global level. Interestingly, air traffic has historically enjoyed growth rates greater than the economic growth rate measured by gross domestic product (GDP) change. Economic cycles coupled with social factors (e.g., pandemics) and political factors (e.g., liberalization of aviation markets and wars) have a significant effect on the demand for air travel, which, consequently, fluctuates over time. One of the key economic factors is the price of crude oil, which impacts airline economics directly through the price of jet

fuel and indirectly through its influence on global economic activity. Fluctuations in the global demand for air travel about the long-term trend associated with economic downturns or other significant events (e.g., terror threats or attacks) have historically been short lived, typically lasting about one year, after which the upward trend has continued.

The demand for air travel is also a function of its cost to the consumer (reduced prices stimulate demand), which, in turn, is dependent on the economic factors that impact airlines. The largest single cost element for airlines in recent years has been aviation fuel, which can represent about half of the total operating cost for a long-haul flight. Airplane fuel efficiency is thus a critically important performance metric for the airline industry; efficient airplanes are essential for airline profitability and long-term economic success of the industry.

Two important environmental considerations for the operation of commercial jet airplanes are noise and engine exhaust emissions. Noise limits for airplane certification are issued by aviation regulatory authorities. In addition, local authorities (e.g., airports) frequently impose additional noise limits. Compliance, in certain cases, can necessitate a noise abatement operational procedure that has performance implications (e.g., a reduced climb thrust setting after takeoff). The environmental impact of airplane emissions is of growing concern. For every 1 kg of jet fuel that is burned in an airplane's engine, approximately 3 kg of carbon dioxide is produced [9]. Increasing airplane fuel efficiency is thus a powerful direct means to reduce the environmental impact of air transport.

1.3 Jet Transport Airplanes: A Short History

What is often referred to as the *jet age* is that fascinating period of aviation history since turbojet engines were first installed on passenger transport airplanes (airliners). The first production jet airliner, the DH 106 Comet, manufactured by de Havilland in the United Kingdom (UK), entered commercial service in May 1952. The airplane offered unprecedented performance. In the cabin, it was quieter than its piston engine counterparts. It was also much quicker and was able to fly higher—thus avoiding bad weather—due to the thrust of its four de Havilland Ghost turbojet engines. The Comet 1, however, was grounded in 1954 when its certificate of airworthiness was withdrawn after two aircraft suffered explosive decompression in flight due to metal fatigue (caused by repeated pressurization cycles).

The first generation of successful turbojet commercial airplane types entered service in the late 1950s. In the Soviet Union, the Tupolev Tu-104 began service with Aeroflot in 1956. The design, which was extensively based on the Tu-16 bomber aircraft, had one Mikulin turbojet engine installed in each wing–fuselage junction. In the UK, deliveries from de Havilland of the extensively redesigned Comet commenced in 1958. The Comet 4 had a longer fuselage than its predecessor (the maximum seating capacity was 81) and more powerful Rolls-Royce Avon engines. In the United States, the Boeing 707 and Douglas DC-8 entered service in 1958 and 1959, respectively. Both types featured four turbojet engines mounted under the airplane's wings. Early variants, however, had limited payload–range capability. In France, Sud Aviation developed the first short- to medium-range jet airliner: the SE 210 Caravelle (later, Sud Aviation merged with Nord Aviation to form Aérospatiale). The design featured two Rolls-Royce RA-29 turbojet engines pod-mounted off the rear fuselage—a configuration that has been extensively used since then in the design of regional jet airplanes.

In the 1960s, newly developed low bypass ratio turbofan engines, such as the Pratt & Whitney JT3D, offered much improved airplane performance. Later variants of the highly successful Boeing 707 and DC-8 types offered true intercontinental capability due to the engine's lower fuel consumption. Convair, a division of General Dynamics, produced the medium-range

Convair 880. Despite its high cruise speed, the airplane failed to attract much interest—this was in part due to its poor economic performance compared to the competition, which included the Boeing 720 (a short-range derivative of the Boeing 707). New types that entered service around the world included the three-engine Boeing 727 and the two-engine Douglas DC-9 (this started a four-decade production run of many derivatives, including the MD-80, MD-90, MD-95, and Boeing 717). Three British airliners entered service in the mid-1960s: the short-range British Aircraft Corporation BAC One-Eleven, the short/medium-range Hawker Siddeley HS 121, and the long-range Vickers-Armstrongs VC10 (which featured a pair of rear-mounted engines on each side of the fuselage). In the Soviet Union, the long-range Ilyushin Il-62, which adopted the same engine configuration as the VC10, commenced service in 1967. The highly successful Boeing 737, featuring twin-turbofan engines installed closely coupled below the wing and a six-abreast seating arrangement, began servicing short- and medium-haul routes¹ in 1968 (to date, more Boeing 737 airplanes have been produced than any other jet airliner). To compete with turboprop airplanes in the regional airplane market, Yakovlev (in the Soviet Union) introduced the small Yak-40 (with 24–32 seats) and Fokker (in the Netherlands) introduced the F28 Fellowship (with 60–65 seats) in 1968 and 1969, respectively.

The 1970s will be remembered as the decade that saw the introduction of widebody airliners, that is, with a fuselage wide enough to accommodate two passenger aisles (typically with seven or more seats abreast). The four-engine Boeing 747, three-engine McDonnell Douglas DC-10, and three-engine Lockheed L-1011 TriStar airplane types began servicing long-haul routes worldwide, with significantly increased payload capacity over the Boeing 707, DC-8, and VC10 types. The Boeing 747 (nicknamed *Jumbo Jet*), which entered service as the world's largest passenger jet in 1970, would remain in production for over 45 years and would dominate this market sector for much of this time. The Tu-154, a narrow-body (i.e., single-aisle) airplane with three rear-mounted engines, began service in 1972. This successful medium-range type, which was designed to operate from unpaved or gravel airfields, saw 40 years of service. The A300, the first product of Airbus Industrie,² entered service as the first twin-engine widebody airplane in 1974. The decade will also be remembered as a time when airports were extremely noisy places. The first noise regulations for subsonic jet airplanes developed by the International Civil Aviation Organization (ICAO) came into force in 1972. These regulations led to the phasing out of many noisy first-generation jet airplanes, while others were modified with hush kits to reduce their noise during takeoff and landing (these modifications inevitably resulted in performance penalties). Noise regulations also spurred the introduction of higher bypass ratio, quieter turbofan engines, such as the General Electric CF6, Pratt & Whitney JT9D, Rolls-Royce RB211, and CFM International CFM56. These engine types and the many derivatives

1 There are no standard definitions of short, medium, or long haul (or range). The terms are used loosely in the aviation industry, with different sectors and organizations defining the categories in their own ways. One definition, used for market categorization, is based on trip duration: short (<3 hr), medium (3–5 hr), and long (>5 hr). Another definition, which is also widely used, defines long haul as a trip time exceeding 6 hr. Ultra-long haul is today taken to mean a flight of more than about 12 hr (although, again, different organizations define it differently). Short haul is sometimes used by airlines to describe domestic or regional routes. When based on distance, short haul is defined by one manufacturer as a trip of less than 3000 miles (2607 nm) and long haul as greater than 4000 miles (3476 nm) [10]. Another definition, which is used in market categorization, defines short haul as a trip distance of less than 2000 nm and long haul as greater than 2000 nm [11].

2 Airbus Industrie, with headquarters in Toulouse, France, was established in 1970 as a consortium of European aerospace companies—a Groupement d'Intérêt Économique (GIE) under French law. Aérospatiale of France, Deutsche Airbus (DASA) of Germany, and Hawker Siddeley of the UK were the initial shareholders. Construcciones Aeronáuticas SA (CASA) of Spain joined soon afterwards. In 2001, following several changes to its structure, the airplane manufacturer became a joint-stock company: Airbus SAS. Airbus's parent company, EADS, was renamed Airbus Group in 2014.

that were subsequently developed based on these designs would power much of the western world's commercial jet airplanes in the decades that followed.

The 1970s also saw the start of supersonic passenger transport services. The Aérospatiale/BAC Concorde—which was operated in small numbers (seven each by Air France and British Airways)—commenced commercial operations in 1976 (the type was retired in 2003). The Russian Tupolev Tu-144 commenced passenger service in 1977 (the fleet was grounded after 55 scheduled flights). Both designs, which were capable of cruising at speeds greater than Mach 2, employed a tail-less, delta wing configuration with four after-burning turbojet engines. Supersonic cruise, however, came at a considerable aerodynamic penalty (the lift-to-drag ratios of these airplanes were less than half that of a typical subsonic airliner), and the fuel efficiency was significantly poorer (a feature that became increasingly apparent as improved, higher bypass ratio turbofan engines were developed for subsonic airliners). Other issues that plagued both Concorde and TU-144 operations were high levels of takeoff noise and the sonic boom (which essentially limited supersonic flight to overwater sectors).

In the 1980s, first and second-generation narrow-body airliners were withdrawn from service in large numbers and replaced by more fuel-efficient twin-turbofan airplanes—these included the newly developed Boeing 757, Boeing 767 (Boeing's first widebody twinjet), and Airbus A310 types. Boeing also introduced the 737-300/-400/-500 models (the so-called Classics), with CFM56 engines and a redesigned, more aerodynamically efficient wing. In the Soviet Union, the Yakovlev Yak-42 and the Tupolev Tu-204 (both narrow-body designs) and the four-engine widebody Ilyushin Il-86 entered service. The Il-96, a shortened longer-range derivative, followed a few years later. British Aerospace, identifying the need for a STOL (short takeoff and landing) airliner, introduced the high-wing four-engine BAe 146 (later variants were called the Avro RJ). The first member of the very successful Airbus A320 family (which includes the A318, A319, A320, and A321 models) began service on short- to medium-range routes in 1988. The type, which was developed as a direct competitor to the Boeing 737, pioneered the use of digital fly-by-wire flight control systems on airliners. The Fokker 100, a 100-seat regional jet with two rear-mounted engines and 5-abreast seating, also commenced service in 1988. A shortened derivative, the Fokker 70, with 70–80 seats, followed a few years later.

In the 1990s, the first *large twins*—widebody twinjets with a maximum seating capacity exceeding *ca.* 300—were introduced into commercial service. The Airbus A330 and Boeing 777—both featuring two high bypass ratio turbofan engines installed below the wings—were able to compete on long-haul transoceanic routes that, in the West, had previously been the exclusive domain of the four-engine Boeing 747 and the three-engine McDonnell Douglas DC-10 and its derivative, the MD-11. This was made possible by new regulations that became known by the acronym ETOPS (initially defined as Extended Twin Operations). Airbus also introduced the long-range four-engine A340, which shared many common design features and components with the A330. In the single-aisle market, the Next-Generation Boeing 737 airplanes entered service (replacing aging Boeing 737 Classics and DC-9/MD-80 airplanes). In the regional jet market, the first variant of the Bombardier (of Canada) CRJ family commenced service in 1992. Embraer (of Brazil) entered this market with the twin-engine ERJ family in 1996 (models include the -135, -140, and -145). The Dornier 328JET, a 32-seat jet-engine commuter manufactured by the American–German Fairchild Dornier, began commercial operations in 1999.

This decade (i.e., the 1990s) also saw much consolidation and reorganization in the aviation industry with, for example, McDonnell Douglas merging with Boeing, and Fokker ceasing production of its own designs. The Lockheed Corporation, which had withdrawn from the civil aircraft business, merged with Martin Marietta to form the defense-orientated Lockheed Martin. The dissolution of the Soviet Union in 1991 significantly affected civil aircraft production in the region, which declined by 80% within a few years; a substantive downsizing and

reorganization of the industry ensued [12]. In Europe, British Aerospace (which, much earlier, had been created by the nationalization and merger of several UK companies, including BAC and Hawker Siddeley) merged in 1999 with Marconi Electronic Systems to form BAE Systems. In the same year, DASA (of Germany), CASA (of Spain), and Aérospatiale-Matra (of France) agreed to merge to create EADS (European Aeronautic Defence and Space Company), which became the majority shareholder of Airbus.

By 2000, Airbus and Boeing effectively shared a duopoly in the large single-aisle and widebody airplane markets (the Tupolev Tu-204/-214 and Ilyushin Il-96 annual production rates were in the low single figures, and the production of the BAe Avro RJ was coming to an end). Following more than 15 years of development effort, Airbus introduced the A380, the world's largest passenger transport airplane (with a seating capacity of 525 passengers in a typical three-class configuration). The A380, a double-deck, widebody, four-engine airliner, began commercial service in 2007. On the other end of the size spectrum, there was much activity in the small single-aisle and regional jet sectors. Embraer, building on their success with the ERJ, introduced the larger E-Jet family in 2004 (models include the E170, E175, E190, and E195). In the Ukraine, Antonov (which had gained worldwide prominence for manufacturing very large military transport aircraft: the An-124 and the one-off giant An-225) developed a new family of high-wing regional jets: the An-148/-158. The An-148 entered service in 2009 after receiving Interstate Aviation Committee (IAC) type certification.

In 2011, the Russian Sukhoi Superjet 100, a low-wing twin-engine regional airliner, began commercial operations with IAC type certification. European certification followed soon afterwards, demonstrating the airplane's compliance with western airworthiness and environmental standards. This opened up international markets for the newly established parent company: United Aircraft Corporation (UAC), a state-owned conglomerate of Russian aerospace companies (including Ilyushin, Irkut, Sukhoi, Tupolev, and Yakovlev). To meet growing international demand for efficient, long-haul operations—and to replace an aging global fleet, which included many four-engine Boeing 747 and Airbus A340 airplanes—both Boeing and Airbus developed new widebody twin-engine airliners: the Boeing 787 entered service in 2011 and the Airbus A350 in 2015. New materials and manufacturing technologies featured strongly in these designs, which made extensive use of carbon fiber composites to reduce airframe weight. In 2016, the Bombardier C Series began commercial operations. This new two-member family of twin-engine medium-range airplanes, comprising the 110-seat CS100 and 135-seat CS300 models, were developed to compete with the Embraer and Sukhoi regional jets and also with the smaller Boeing 737 and Airbus A320 airplane types. In the same year, the Chinese Comac ARJ21-700, a 90-seat single-aisle twinjet with a resemblance to the MD-80, commenced domestic service with Chinese type certification. The next airplane program for this state-owned manufacturer is the single-aisle twin-engine C919. Also competing in this market, on completion of development, will be the UAC Irkut MC-21. Japan's first passenger jet airplane, the 70–90 seat Mitsubishi MRJ, commenced flight testing in 2015, with an entry-into-service target of 2020. The decade (i.e., the 2010s) also saw Airbus and Boeing launching new versions of their single-aisle airplanes—that is, the Airbus A320neo family (first deliveries in 2016) and the Boeing 737-MAX family (first deliveries in 2017). New engine technologies (in the CFM International LEAP and Pratt & Whitney PW1000G turbofan engines) and aerodynamic refinements were key elements of these improved versions of the industry's two best-selling jet transport airplanes.

Although superficially similar in appearance to the jet airliners of the 1960s in terms of their primary geometry—that is, featuring a tubular fuselage with rear empennage, swept wing, and pod-mounted engines installed either under the wing or on the rear fuselage—the latest generation of airliners have many advanced structural, aerodynamic, system, and engine design features that enable them to operate at much improved fuel efficiency levels compared to the

early generation jet airliners. Using the Comet 4 as a baseline, these airplanes are more than 70% more fuel efficient per available seat kilometer (ASK) [13]. Noise levels and exhaust emissions have also been significantly reduced over this time. Overall reliability, passenger comfort, and safety³ have all been dramatically improved.

1.4 Regulatory Framework

The performance of commercial jet transport airplanes needs to be considered within the context of the regulatory framework that applies to the certification and subsequent operation of these aircraft. In the United States (US), these regulations are issued by the Federal Aviation Administration (FAA); equivalent European specifications are issued by the European Aviation Safety Agency (EASA). Additionally, the national aviation authorities of individual countries with significant aviation industries publish their own regulations. In a colloquial setting, these regulations are often referred to as *the rules*. Although substantially similar in many respects, important differences exist between various sets of regulations. Herein, only the US and European regulations are considered. The key documents and the organizations responsible for these measures are described in Chapter 23.

For the purpose of certification and operation, airliners fall within the *transport* category of aircraft. As regards airplane *certification*, key regulations include the US Federal Aviation Regulation Part 25 [15], usually abbreviated as FAR 25, and the European counterpart, EASA Certification Specification 25 (Book 1) [16], abbreviated as CS-25. In many instances, these regulations are identical (the result of many years of effort to harmonize technical details). Common regulations are often written as FAR/CS 25—a practice that has been adopted herein. As regards the *operation* of these airplanes, important regulations are the US Federal Aviation Regulation Parts 91 [17] and 121 [18] and European EASA OPS Part-CAT [19].

The certification of a new airplane involves an extensive series of tests and compliance checks designed to ensure that it meets a minimum set of safety standards. FAR/CS 25 [15, 16] contain specific requirements that pertain to an airplane's performance, which must be demonstrated during the certification process. For example, FAR/CS 25.121(a) deals with an airplane's ability to climb following takeoff with one engine inoperative and with the landing gear extended. It is stipulated that the steady gradient of climb must be positive for two-engine airplanes, not less than 0.3% for three-engine airplanes, and 0.5% for four-engine airplanes, in the critical takeoff configuration. Compliance has to be demonstrated at the appropriate airplane weight, without the benefit of ground effect, with the critical engine (i.e., the engine that most adversely affects the airplane's climb performance) inoperative at a specified speed and thrust setting. This is one of many such performance requirements defined in FAR/CS 25. Airplanes that meet these requirements will have demonstrated a minimum performance capability that is considered appropriate for safe flight operations.⁴

An important output of the certification process is a formal record of the key safety-related performance capabilities of the airplane—this is the Airplane/Aeroplane Flight Manual (AFM). As the AFM is not designed to be used by flight crews, another document, known as the Flight Crew Operations/Operating Manual (FCOM), is produced based on the same performance data, but supplemented by approved manufacturers' data concerning non-safety-critical

³ The global accident rate for civil jet airplanes for the five-year period 2010–2014, measured in hull losses per 1 million flights, was 0.45; this is the equivalent of one major accident for every 2.2 million flights [14].

⁴ Acceptable methods to demonstrate compliance with the primary certification requirements/standards are given in FAA Advisory Circular (AC) 25-7 [20] and EASA CS-25 (Book 2) [16].

topics, such as optimum cruise speeds and all-engine climb performance. The FCOM is the primary source of performance information used by flight crews, who must operate their airplanes within a highly regulated environment, which is a feature of commercial aviation.

The rules that apply to commercial flight operations are many and varied, and these impose yet another set of constraints or limits on the performance that an airplane might achieve in routine flight operations. The International Civil Aviation Organization (ICAO) is responsible for coordinating and regulating international air travel. Central to this role is the Convention on International Civil Aviation [21], which, together with the many standards, policies, and procedures issued by ICAO, provides an internationally agreed framework for the safe operation of aircraft. This includes a set of procedures for operating within controlled airspace. It is often necessary to consider these procedures when analyzing an airplane's performance. Flight altitudes can be restricted and speed restrictions are imposed below 10 000 ft in much of the airspace used for commercial operations worldwide. These factors impact an airplane's achievable performance in service—for example, the previously mentioned restrictions can influence the time that it would take an airliner to reach its initial cruise altitude.

1.5 Performance-Related Activities

1.5.1 Performance Activities Related to the Airplane Life Cycle

Performance analyses are conducted for a variety of reasons, and the techniques that are used vary depending on the nature of the problem—for example, there is the prediction of the performance of a new airplane at the design stage; the reduction of flight-test data from a test airplane; the generation of performance data for the AFM and other key documents; the planning of flight operations taking into account real operational conditions; and the *in situ* calculations and performance monitoring undertaken by the flight crew during flight. Four distinct sets of activities that involve elements of airplane performance are identified in Figure 1.1. The activities have been arranged in the sequence in which they would first be conducted for a new airplane—that is, through the airplane's life cycle. For each activity, the physics does not change as the underlying principles of flight dynamics are the same, but the nature of the work undertaken is different as the purpose—and available data—of each activity is different. Although different calculations are carried out during the different activities, the theoretical basis for the various analyses that are conducted is largely the same.

During the design of a new airplane, engineering analyses are conducted where the performance targets—such as payload–range capability, cruise speed, fuel efficiency, and takeoff and landing capability—have been established, and the airplane's design features and aerodynamic characteristics are to be determined. At the conceptual design stage, it is usual to make a number of simplifying assumptions concerning the behavior of the airplane and regarding the operating environment, which will facilitate analytical solutions to be obtained for many performance problems. The techniques would only need to be accurate to within a few percent. In later stages of the design process, where more accurate performance predictions are required—and more data on the new design are available—more sophisticated techniques, which often involve numerical computation, are likely to be used.

The flight testing and subsequent data analyses of a new airplane type—which establishes the airplane's validated, or demonstrated, performance characteristics—involve a different set of analysis techniques and methodologies. Performance characteristics of the airplane are measured and compared to predicted values. As a range of air temperature and pressure conditions are typically encountered during flight testing, measured performance data are adjusted to

Airplane design (by the manufacturer)

Activities include performance analyses conducted using projected airplane data (e.g., airplane geometry, weight, aerodynamic and engine characteristics) using idealized mathematical models and historical data in support of design activities associated with the development of a new airplane (or a derivative). Primary considerations include: (1) airworthiness regulations (e.g., FAR/CS 25); (2) operational regulations (e.g., FAR 121, EASA OPS Part-CAT); and (3) customer requirements (e.g., payload–range capability, takeoff and landing distances, fuel economy).

Flight testing and generation of performance documentation (by the manufacturer)

Activities include the measurement of airplane performance characteristics during a series of standardized tests (described in FAA AC 25-7 and EASA CS-25 Book 2, for example), conducted in actual conditions (not idealized or model conditions) using test airplanes with extensive airborne and ground instrumentation.

Analysis of flight test and supporting performance data is conducted (1) to demonstrate compliance with the regulations (e.g., FAR/CS 25); (2) to produce the Airplane Flight Manual (AFM); and (3) to validate design characteristics and produce data that can be used by the manufacturer and operator.

Data are corrected to standard conditions (e.g., ISA). Correction factors are introduced for flight operations (e.g., to account for anticipated differences in reaction times between test pilots and line pilots in emergency situations, such as engine failure).

Operational documentation (e.g., FCOM) is generated, which must (1) consider likely operational conditions (e.g., off-ISA conditions, airfield limits); (2) introduce conservative correction factors and allowances (e.g., credit for headwind on landing); and (3) establish operational limit speeds (e.g., minimum control speed in the air).

Performance engineering (by the operator)

Operational flight planning activities are conducted in accordance with (1) the manufacturer's documentation (e.g., AFM); (2) the requirements of the regulatory authorities (e.g., FAR 121 and EASA OPS Part-CAT); and (3) local and international restrictions (e.g., noise limits). Activities include route planning (for standard and emergency conditions), the analysis of the airplane's performance for all critical phases of the flight, the determination of fuel requirements, weight and balance calculations, and takeoff and landing performance estimations (addressing such issues as noise abatement and reduced thrust, if applicable).

Flight operations (by the flight crew)

Flight operations are conducted in actual (non-idealized) weather conditions; hence corrections to published performance data may be required.

Preflight activities include the determination of the fuel required for the flight; checking of weight and center of gravity position against airplane limits; route planning (which considers forecast winds, weather, and anticipated delays); and airplane condition (e.g., restrictions due to unserviceable items).

In-flight activities include operating the airplane within the manufacturer's performance limits (e.g., speed, load factor, angle of attack), fuel status and systems monitoring, and the management of routine and emergency situations.

Figure 1.1 Airplane performance-related activities.

represent the data as a function of pressure altitude, which is based on the idealized conditions defined in the International Standard Atmosphere (ISA). Airspeed and altitude instrumentation is calibrated to sea level (datum) conditions of the ISA. The database that is produced through the flight-test program is used to generate the performance values that are recorded in the AFM.

The determination of safety-related performance data during flight testing is a key part of the certification process in which compliance with the relevant airworthiness regulations must be demonstrated for the issue of a *type certificate*. Individual aircraft manufactured to an approved design—that is, a design for which a type certificate has been granted—may be issued a *certificate of airworthiness* by the national aviation authority of the country in which the airplane is registered. Airplanes with a valid certificate of airworthiness (which requires annual renewal) may be legally operated within the regulatory conditions of its issue.

The safe operation of any aircraft depends critically on the relevance and accuracy of the performance data that are available to the operator and flight crew. Performance calculations conducted in support of flight operations are based on manufacturers' performance data—taking account of the forecast weather, prevailing winds, runway conditions and limits, obstacle heights, and so forth. In some respects, the nature of these calculations is the reverse of that conducted during the design of the airplane: here, the airplane's performance attributes have to be determined based on known airplane characteristics; whereas during the design phase, it is the airplane characteristics that have to be determined to meet performance targets.

1.5.2 Performance Engineering and Flight Operations

There is a diverse set of engineering tasks and activities associated with the in-service operation of a commercial jet transport airplanes that is customarily addressed under the heading of *airplane performance engineering*. The list of activities undertaken by performance engineers in support of flight operations can, for the sake of convenience, be grouped under five headings, although in reality there are many overlapping aspects. The description given below is not intended to be exhaustive, but rather illustrative of the nature of this work—these descriptions serve to establish a backdrop to the discussions presented in this book.

Performance Activities Associated with Specific Phases of a Flight

These activities include the determination and monitoring of the performance of an airplane during specific phases of the flight, which include takeoff (and rejected takeoff), initial climb after takeoff, takeoff flight path, *en route* climb to cruise altitude, cruise (including step climb), descent, approach (and missed approach), and landing. Key tasks are associated with establishing the airplane's performance during emergencies, such as engine failures at any stage of the flight and the determination of associated operational procedures.

Trip/Mission Performance

These activities consider the trip, or mission, performance of an airplane, which include payload–range assessments, determination of cost index parameters, policies for fuel tankering (fuel transportation), fuel conservation (including policy development and implementation), and considerations associated with exhaust emissions.

Route and Operational Flight Planning

These activities are associated with route analysis and consider such issues as foreign and domestic airspace restrictions, available air traffic tracks and flight levels, air traffic control (ATC) restrictions, suitability of destination and alternate airports, fuel considerations (including fuel planning and fuel usage monitoring), *en route* terrain considerations (including the determination of minimum safe altitudes), in-flight emergency considerations (e.g., oxygen requirements for passengers and crew), and extended-range twin-engine operations.

Weight and Balance

These activities are associated with establishing the airplane's operating empty weight (OEW) and center of gravity (CG) location, developing load sheets and validating payload weight procedures, assessing the CG location with respect to the manufacturer's fore and aft limits for each phase of the flight, and establishing procedures for the correct setting of the stabilizer trim for takeoff.

Operational Support and Organization-Specific Tasks

These activities include the preparation and upkeep of documentation for flight crews and dispatchers; implementation of applicable service bulletins, airworthiness directives and regulations; maintaining dispatch deviation documents (e.g., Master Minimum Equipment List); and a wide range of performance tasks applicable to the individual organization (e.g., monitoring reduced thrust usage in takeoff or climb, and providing input to fleet retirement/renewal decisions).

1.6 Analysis Techniques and Idealizations

The analysis techniques that are used to compute the performance characteristics of an airplane vary considerably depending on the purpose and the availability of data. There are many cases where a quick, simple "back of the envelope" calculation will suffice in order to obtain an approximate answer—for example, to provide a cross check against a result produced by a computer program or data contained in a reference manual. Simple, approximate methods also get used in student exercises, where real airplane data are seldom available. More sophisticated methods are, of course, needed for the computation of performance values that would be used in planning actual flight operations. In this book, a variety of methods of varying degrees of complexity are described (note that certain of these methods are only suitable for rough estimations).

Airplane performance analyses, in most cases, rely on three sets of data—these correspond to descriptions of (1) the characteristic parameters of the airplane (e.g., geometric parameters such as the wing reference area, aerodynamic relationships such as the drag polar, and the airplane's gross weight⁵ and center of gravity position); (2) the characteristic parameters of the engine (e.g., net thrust and rate of fuel consumption); and (3) the environment in which the airplane is operating (e.g., ambient air temperature and pressure, wind, and runway features for takeoff and landing calculations). For example, the determination of an airplane's instantaneous rate of climb corresponding to a set of conditions (e.g., airplane gross weight, altitude, air temperature, speed, and acceleration) will require knowledge of a subset of data from the three groups, and—as will be shown later—the rate of climb depends principally on the airplane's thrust and drag.

The task of analyzing the airplane's performance is greatly simplified by the establishment of analytical models. Note that these models are not absolute laws, although many have a theoretical basis. These mathematical models are approximations of measurable parameters, which are usually only valid within specified limits. Some of these relationships can be described by surprisingly simple polynomial functions (such as the parabolic drag polar), which are adequate for approximate calculations. Certain functions, however, do not lend themselves to simple mathematical idealization. The variation of thrust lapse rate with altitude and speed, for example, is far too complex to be modeled by simple functions. Mathematical models can often be extremely useful, as they permit "exact" solutions to be found for complex scenarios, thus enabling

⁵ *Gross weight* is the total airplane weight at any moment during the flight or ground operation (i.e., instantaneous weight).

sensitivity analyses to be completed, thereby identifying the relationship between changes in airplane characteristic parameters and the predicted performance. Quite often, simple mathematical expressions can be used to initially study an idealized problem, and, thereafter, the effect of discrepancies between the model and reality can be addressed by adding smaller, second-order terms or correction factors to refine the calculation.

Idealizations are widely used in airplane performance studies. For most applications, the airplane can be considered to be a rigid body, permitting a classical Newtonian mechanics approach to be used to determine the equations of motion of the airplane. The application of static air loads on the wing will alter the wing's shape as it bends upwards and twists, resulting in a change to the chordwise and spanwise lift distributions, which will change the lift-induced drag. This can, in part, be accounted for in the determination of the airplane's drag polar. Dynamic air loads due to gusts (which tend to be oscillatory) momentarily influence the airplane's trajectory, but have a negligible influence on such performance parameters as climb gradient, range, or endurance.

For certain performance analyses that are associated with point calculations, it is often convenient to assume that a quasi-steady-state condition exists. The airplane's velocity vector is thus assumed not to change in magnitude or direction. This implies a state of equilibrium and a balance between the forces of lift, drag, thrust, and weight, which greatly simplifies the mathematics. Considering, once again, the example of instantaneous rate of climb, such an idealization would ignore the influence of the rate of change of true airspeed with height as well as the influence of wind gradients. In this case, the assumption of quasi-steady state permits the determination of a reasonable approximation. The inclusion of the first acceleration term will provide a small refinement to the calculation; the second acceleration term (i.e., due to a wind gradient) has an even smaller influence on the computed answer for a typical *en route* climb.

Another idealization that is frequently adopted when computing a performance parameter that relies on a time-based integral assumes that the airplane's mass is constant. This is obviously not true for a jet airplane due to the continuous consumption of fuel. However, the time rate of change of the airplane's mass is small, and this permits certain performance analyses to be conducted with the assumption of constant airplane mass. For example, it is commonplace to assume that the airplane's mass does not change during the takeoff run. This assumption simplifies the mathematics and facilitates the development of a closed-form mathematical solution for the takeoff run. Nonetheless, the inclusion of mass change is possible within a sophisticated numerical routine that involves an iterative approach to the determination of the takeoff distance, and this provides a means to refine the computed distance—albeit by a very small amount.

The Earth's curvature is an important consideration for long distance navigation, but, for the most part, the performance of an airplane can be satisfactorily assessed by assuming that the Earth is flat. Additionally, the Earth's rotation does not have a significant influence on most performance parameters and is generally ignored. There are, however, certain times when a high degree of precision is warranted and it is justified to take into account small correction factors. For example, in the analysis of specific fuel consumption data recorded during flight tests, it is possible to take into account the centrifugal influence of the Earth's rotational velocity on the airplane's weight—this correction depends on the airplane's ground speed and direction of flight (or, more precisely, its true track).

A common engineering approach, when assessing the validity of such idealizations, considers the impact that the idealization has on the computed result. For example, when credit is not taken for the reducing airplane mass during takeoff, a conservative result is obtained—that is, a marginally longer takeoff distance is predicted—and this may justify the use of the idealization. Another factor that must always be considered when assessing the merits of including

such refinements is the accuracy to which the other parameters in the equation can be established. There is little value in going to considerable computational effort (e.g., by accounting for aircraft mass change in a takeoff analysis) when there is uncertainty associated with another parameter in the equation that has a significantly greater influence on the final result.

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