Appendix D

Basic Concepts of Performance-Based Navigation (PBN) and Air Traffic Control (ATC)

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List of Acronyms

ADF	Automatic Direction Finder
AGL	Above ground level
ATC	Air traffic control
ATO	Air Traffic Organization
CO_2	Carbon dioxide
FAA	Federal Aviation Administration
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IAP	Instrument approach procedure
IFPs	Instrument flight procedures
IFR	Instrument flight rules
ILS	Instrument landing system
MSL	Mean sea level
NAS	National Airspace System
NAVAIDs	Navigational aids
NDB	Nondirectional beacon
NextGen	Next Generation Air Transportation System
NM	Nautical mile(s)
NO_x	Nitrogen oxide
NPAs	Non-precision approaches
ODP	Obstacle Departure Procedure
OPC	Optimized profile climb
OPD	Optimized profile descent
PAs	Precision approaches
PBN	Performance-Based Navigation
RNAV	Area Navigation
RNP	Required Navigation Performance
RNP AR	Required Navigation Performance with Authorization Required
SIDs	Standard Instrument Departures
STAR	Standard Terminal Arrival Route
VFR	Visual flight rules
VOR	Very high frequency omnidirectional range

The Federal Aviation Administration (FAA) was established as a result of the 1958 Federal Aviation Act to provide consistent regulation for aviation safety and airspace management throughout the United States and to ensure the safety and efficiency of aviation operations. Its regulatory activities include licensing aircraft and their operators, providing and managing standards for operator training, aircraft operation, and equipment manufacturing, and controlling and managing the use of navigable airspace within the United States. To achieve this aim, the FAA provides air traffic services to manage takeoffs, landings, and en route flight between airports through the use of air traffic control (ATC) facilities and infrastructure, staff, and navigational and communications technology systems, including a system of navigational aids (NAVAIDs) that allow aircraft operations to occur without visual reference to the ground.

As demand for air travel increased, the National Airspace System (NAS) experienced growing congestion, challenges, and concerns, including airspace capacity, limitations of the existing NAVAID system, and safety and efficiency goals. Airspace modernization activities began in the 1960s and have continued steadily since then, leading up to the creation of the FAA's Air Traffic Organization (ATO) in 2003, a performance-based organization dedicated to the safe and efficient operation of the ATC system. Shortly thereafter, in 2004, the FAA began to investigate and implement new concepts to increase system capacity, reduce flight and schedule disruptions, and enhance safety. These concepts included Area Navigation (RNAV) and Required Navigation Performance (RNP), which together enable Performance-Based Navigation (PBN) flight procedures.

PBN encompasses a wide range of technologies that allow aviation to move from reliance on ground-based NAVAIDs towards navigation enabled by aircraft performance and on-board equipment capability. The use of PBN flight procedures allows for more precise, direct, and efficient flight routes, increased airspace capacity, more flexibility in procedure design, and reduced reliance on ground-based NAVAIDs.

Since the Phoenix Area FAA Modernization Project Environmental Assessment involves improvements and modernization to the airspace system, this appendix provides a basic overview of ATC terminology and helpful descriptions of the NAS.

D. AIR TRAFFIC CONTROL IN THE NATIONAL AIRSPACE SYSTEM

The ATC system maintains safe and orderly flight operations by separating aircraft operating within defined sectors of airspace under the control of air traffic controllers. During all phases of flight, aircraft operate within the NAS in either controlled or uncontrolled airspace. In controlled airspace, ATC provides safe and adequate separation between flight operations. In uncontrolled airspace, ATC does not provide separation services because it does not manage that airspace.

D.1 Airspace Classes

Controlled airspace includes several classes of airspace in which ATC actively directs and separates aircraft to ensure safety. Controlled airspace is typically found around busy airports and at higher flight levels where commercial and instrument flights operate. Pilots must receive ATC clearance to enter controlled airspace and maintain communications with ATC while within the airspace (FAA 2023).

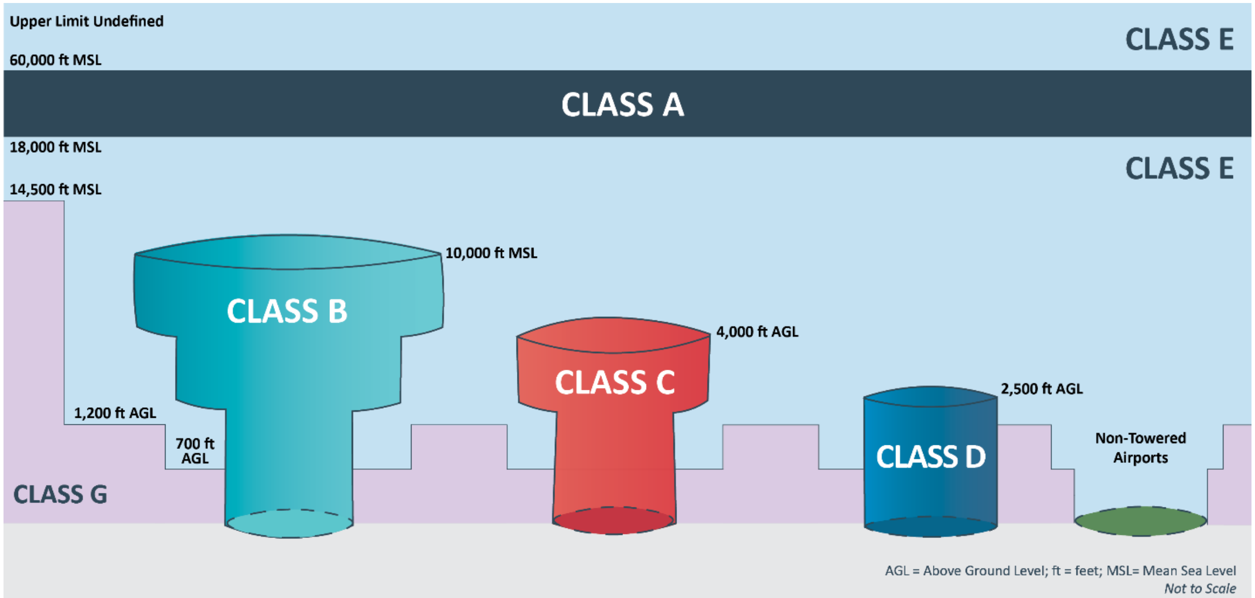
The types of controlled airspace are:

- **Class A (Alpha)**: Extends from 18,000 feet mean sea level (MSL) to 60,000 feet MSL. Pilots must operate under Instrument Flight Rules (IFR) and receive ATC clearance before entry.
- **Class B (Bravo)**: Surrounds the nation's busiest airports and extends from the surface to 10,000 feet MSL. The shape of Class B airspace is often referred to as an inverted wedding cake, as it contains several stacked layers of airspace with increasing width. Class B airspace is designed to contain all published instrument procedures for the primary airport. Operating within Class B airspace requires ATC clearance, two-way radio communication, and a Mode C transponder.
- **Class C (Charlie)**: Surrounds moderately busy airports and extends from the surface up to approximately 4,000 feet Above Ground Level (AGL). It includes two levels: an inner 5-nautical mile (NM) radius from the airport's surface to 4,000 feet AGL, and an outer 10-NM radius extending from 1,200 feet AGL to 4,000 feet AGL. Two-way radio communication must be established with ATC before entry.
- **Class D (Delta)**: Found at airports with an active control tower that are not Class B or Class C airports. Class D airspace extends from the surface to 2,500 feet AGL and is usually a simple cylinder. Pilots must establish two-way radio communication with ATC before entry.
- **Class E (Echo):** Encompasses the remaining controlled airspace, generally extending from 1,200 feet AGL up to 18,000 feet MSL. Depending on the need to protect other airspace, Class E airspace may begin at 700 feet AGL or at the surface near some airports. ATC services are available in Class E airspace, but radio communication is not required for Visual Flight Rules (VFR) operations.

Exhibit D-1 provides a visual overview of how the NAS is structured.

Uncontrolled airspace (Class G) covers all airspace not designated as controlled airspace and generally extends from the surface to the base of the overlying Class E airspace. In uncontrolled airspace, ATC does not provide separation, and services are limited to advisories upon request. Pilots are responsible for their own navigation and collision avoidance (see-and-avoid) and must follow VFR minimums. No clearances or radio communications are required to operate in Class G airspace, but pilots can use a common radio frequency to communicate their intentions to other nearby pilots.

Exhibit D-1. Types of Airspace



Source: HMMH 2025

D.2 Phases of Flight

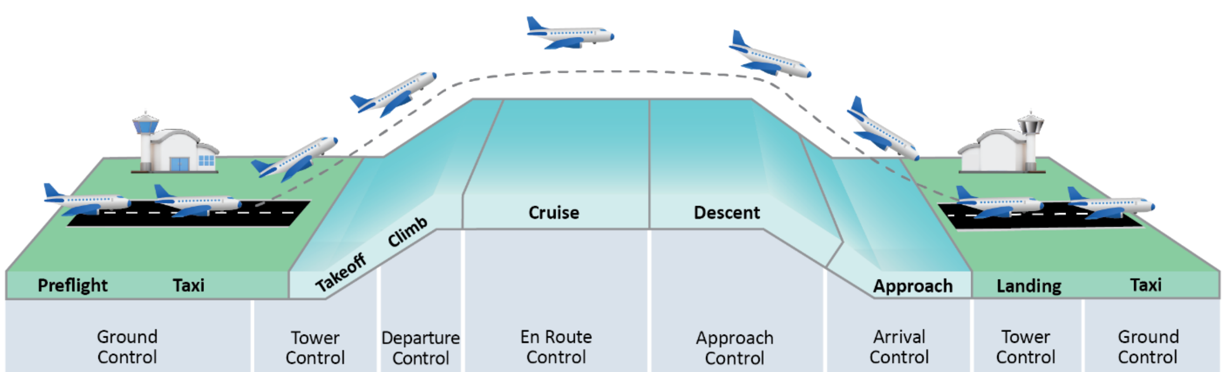
Aircraft traveling between two airports pass through nine phases of flight (ICAO CAST 2013). For commercial aircraft, transitions between these phases include "handoffs" between different air traffic control facilities. These handoffs occur at defined transfer control points, usually at the boundaries between two adjacent facilities, and pass responsibility for an aircraft from one controller to the next. The nine phases of flight include:

- **Preflight Planning/Preparation**: Occurs before the aircraft moves and involves reviewing the flight plan (route, weather, fuel), performing safety inspections, and confirming weight and balance limits.
- **Taxi**: Movement of the aircraft on the ground—from gate to runway—under its own power or using a pushback tug. This phase is managed by the airport's ground controller, with a transfer to tower control prior to takeoff.
- **Takeoff**: Acceleration of the aircraft down the runway, rotation (lifting the nose wheel), and initial lift-off into the air. During this phase, the aircraft is under control of the airport's tower controller. ATC provides takeoff clearance and specific instructions for separation from other aircraft after takeoff. These instructions may include the use of defined departure procedures, known as Standard Instrument Departures (SIDs), that simplify workload levels for pilots and controllers.
- **Climb**: The aircraft climbs to its designated cruising altitude. During initial climb, pilots retract the landing gear and flaps and transition the engine to climb power settings. They may also continue to follow a SID, if one was assigned. Responsibility transfers from the tower control to departure control and the aircraft may pass through more than one departure sector during its climb.

- **Cruise**: The longest portion of the flight, where the aircraft maintains a steady, high altitude and speed to its destination. Air traffic control transfers from departure control to en route control for this phase.
- **Descent**: The gradual decrease in altitude from the cruising level toward the destination airport. During this phase, the pilots may be assigned a Standard Terminal Arrival Route (STAR) to aid in sequencing and coordination through the airspace sectors. The aircraft is managed by approach controllers at terminal ATC facilities.
- **Approach**: To prepare for landing, the pilot aligns the aircraft with the runway, reduces speed, and configures flap and landing gear. Pilots may follow an Instrument Approach Procedure (IAP), which provides lateral and, in some cases, vertical guidance to the runway and protection from obstacles during the approach. Air traffic control may transfer between one or more arrival controllers before transferring to the arrival airport tower controller.
- **Landing**: The aircraft touches down on the runway and decelerates using spoilers and reverse thrust. The tower controller oversees this phase.
- **Taxi**: After vacating the runway, the aircraft taxis to the gate under the direction of the airport's ground controller, following a handoff from tower control at a defined point specified by airport ATC protocols.

Exhibit D-2 illustrates these phases and associated ATC responsibilities.

Exhibit D-2. Phases of Flight



Source: HMMH 2025

D.3 Aircraft Separation

Separation services are provided via a combination of equipment, procedures, and personnel. Procedures are used to provide repeatable, standardized operations within the NAS. The equipment—including radio services, NAVAIDs, transponders, and surveillance—enable the use of these procedures, and air traffic personnel provide directions and separation instructions to aircraft operators.

Prior to the advent of the ATC system, aircraft operators separated themselves from other aircraft and obstacles by visually identifying such impediments and altering course to avoid them. This method, known as see-and-avoid, is still used today and forms the basis of VFR separation. However, operations in clouds or in periods of limited visibility require IFR separation, which uses different separation techniques, relying on ATC personnel, procedures, and equipment to provide safe separation between aircraft. As operations increased, particularly around busy airports, IFR procedures were implemented to expedite operations and reduce workload for both operators and controllers when operating in controlled airspace. Operating under IFR requires an additional layer of training in addition to a basic pilot's or operator's license. Today, most commercial operations are IFR operations and are under the jurisdiction of ATC throughout all stages of flight.

D.3.1 Separation Requirements

FAA separation requirements are defined in FAA JO 7110.65 (FAA 2025a)[1] and depend on several factors, including aircraft distance from a radar, aircraft class and weight, and airspace. Aircraft are considered to be adequately separated if either horizontal or vertical separation minimum requirements are met; for a loss of separation event, both vertical and horizontal separation requirements must have been violated.

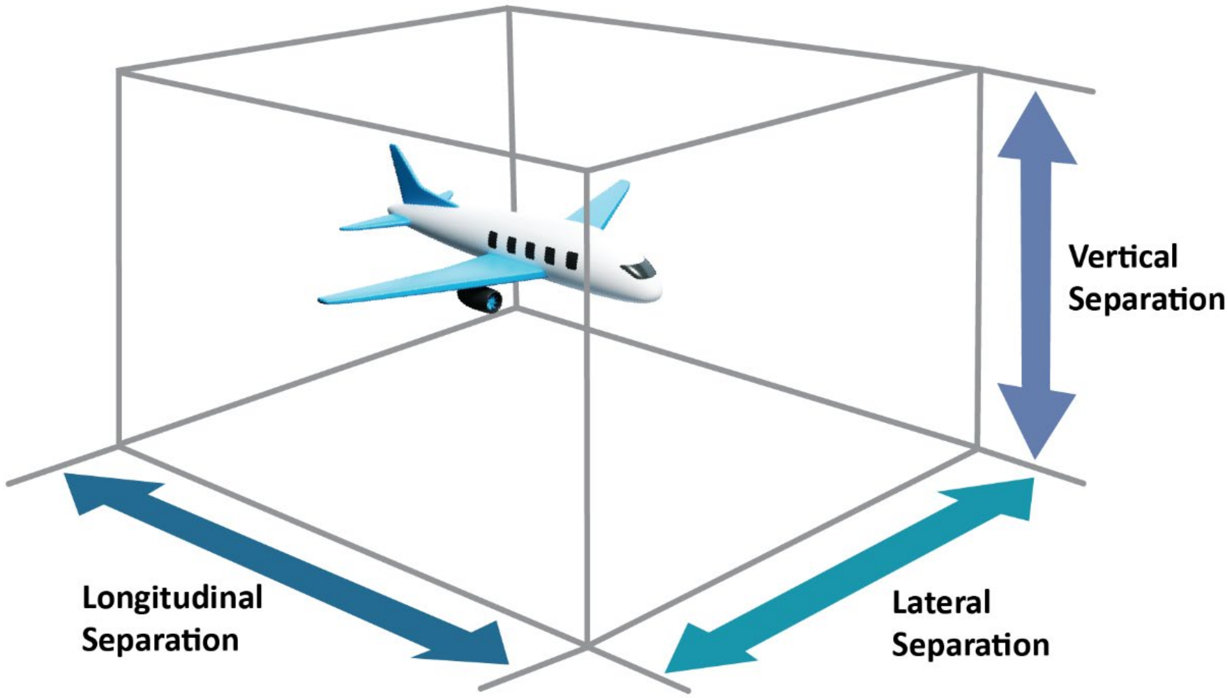
The following types of separation and their general minimums are:

- **Longitudinal or "in trail" separation:** Refers to the distance between one aircraft following another. Separation minimums for aircraft in trail range from 2.5 NM to 10 NM and vary with the type of airspace, aircraft distance from radar, aircraft characteristics, and ATC operational conditions and equipment.
- **Vertical separation:** Refers to the altitude difference between two aircraft, with the minimum separation distance for IFR aircraft being 1,000 feet for operations up to 41,000 feet above MSL. At or above 41,000 feet MSL, aircraft are generally separated by 2,000 feet. Exceptions exist for supersonic, military, and VFR operations.
- **Lateral separation:** Refers to the side-by-side distance of two aircraft. Per JO 7110.65, lateral minimums depend on aircraft distance from a radar. For aircraft within 40 NM of a radar, lateral separation is 3 NM; for aircraft 40 NM or farther from a radar, separation is 5 NM.

Exhibit D-3 illustrates the three types of separation.

[1] FAA JO 7110.65BB is the current version and was published on February 20, 2025.

Exhibit D-3. Types of Separation



Source: HMMH 2025

D.3.2 Separation Methods

Air traffic controllers use several methods to achieve adequate separation between aircraft. These methods include:

- **Speed Control**: Controllers assign increases or decreases in aircraft speed to manage separation distances between aircraft.
- **Altitude Assignments**: Controllers use assigned altitudes to vertically separate aircraft.
- **Routing/Flight Plan**: Different routes and airways are used to laterally separate aircraft at similar or converging altitudes. Changes to routings are also used to avoid weather, airspace, or other factors that could affect safe flight operations.
- **Vectoring**: Controllers may assign temporary headings to maintain separation between other aircraft and/or obstacles. As with routing changes, vectors can be used to avoid weather, airspace, or other impediments.
- **Holding**: Holding is used to maintain separation and manage traffic volume in upcoming airspace. Controllers assign holding patterns to airborne aircraft or hold aircraft on the ground prior to departure.

D.4 Instrument Flight Procedures

Instrument Flight Procedures (IFPs) formalize and publicize sets of instructions to provide safe, efficient transition of IFR aircraft through terminal airspace during departure or approach and landing. These procedures allow aircraft to safely depart or arrive at an airport in potentially hazardous or challenging situations, such as poor weather, limited visibility, or adverse terrain or obstacles, by defining a safe, three-dimensional flight path and providing horizontal, lateral, and vertical guidance along it. IFPs include three distinct kinds of procedures (FAA 2017):

- SIDs are developed to facilitate efficient air traffic management and obstacle and terrain avoidance on departure.
- STARs facilitate air traffic management of arrival traffic in a terminal area.
- IAPs enable safe descent of aircraft through inclement weather (limited visibility and clouds) and/or challenging terrain to the runway environment.

IFPs are charted and/or textual descriptions of a course or route to be flown, minimum and/or maximum altitudes to be observed, and similar procedural information that, when followed by pilots, facilitates separation of aircraft from other aircraft and from terrain while operating under IFR. Components and information required to define an IFP include the type of procedure; the type of NAVAIDs required to execute the procedure; courses, headings, and distances to fly; altitude specifications; and waypoints or fixes.

Waypoints and fixes are geographic points defined by ground-based or space-based NAVAIDs. Conventional IFPs use waypoints and fixes defined by ground-based NAVAIDs, which use radio frequencies to provide guidance to or from them. PBN procedures use space-based, or Global Positioning System (GPS), NAVAIDs and thus are not limited by the physical space or the maintenance required to support conventional NAVAIDs.

D.4.1 Standard Instrument Departure Procedures

Instrument departure procedures are IFR procedures that provide lateral and vertical guidance along a common route when leaving the terminal area on the way to join an en route structure such as an airway. The three-dimensional flight path defined by a departure procedure separates a departing aircraft from other traffic, obstacles, and hazards in the area. Departure procedures can either be an Obstacle Departure Procedure (ODP) or a SID. An ODP provides obstacle clearance during departures. When one exists, it is the default IFR departure procedure for that runway. This ensures that pilots are aware of the obstacle(s) and the ODP is used if air traffic control does not provide vectors or assign a SID. They do not need to be assigned by ATC to be used.

The need for an ODP for a runway is assessed as part of the initial development of an IAP. If an aircraft can turn in any direction after departure within the defined assessment area and remain clear of obstacles, an ODP is unnecessary. ODPs are designed to provide the least restrictive flight path to a position where obstacles or other restrictions to flight no longer impede free flight. While they provide obstacle clearance guidance, they do not provide climb guidance. Though one or more SIDs may exist in addition to the ODP, only one ODP is available for a given runway and only if that runway has an IAP associated with it (FAA 2017).

A SID can be requested by a pilot or assigned by air traffic controllers and is often used at airports operating within busy terminal areas. The intent of these procedures is to increase efficiency and capacity of the airspace by reducing pilot and controller workloads through common procedures, simplified clearances, and reduced communication needs. The SID allows a flight to depart a terminal area in the desired direction of flight via a defined route, using defined speeds, altitudes, and distances. These defined characteristics allow air traffic control to integrate the departing aircraft into the en route flows more effectively and efficiently.

D.4.2 Standard Terminal Arrival Route Procedures

A STAR is used by IFR aircraft arriving at a certain airport and specifies the route, altitude, and speed the aircraft will fly during the arrival phase of flight. A STAR may include several feeder routes, or en route transitions, that allow an aircraft to join an approach procedure for a specific runway.

As with SIDs, STARs simplify communication and understanding between the pilot and air traffic control by providing a transition between the en route and the final, or approach, phase of IFR flight. It places flights on a known, consistent path, allowing air traffic control to sequence aircraft more easily and efficiently for arrival.

D.4.3 Instrument Approach Procedures

An IAP is a defined procedure that allows aircraft under IFR to transition from the en route flight environment of airways and air routes to the initiation of landing procedures in the terminal environment. Such a procedure consists of defined maneuvers with reference to flight instruments that provide protection from obstacles, air traffic, and other hazards, providing safe and predictable transition to a point where the runway can be acquired and landing can be completed.

Two categories of IAPs are available to pilots: a two-dimensional IAP that provides flight path and lateral guidance, known as non-precision approaches (NPAs), and a three-dimensional IAP that provides flight path, lateral, and vertical guidance, or precision approaches (PAs). IAPs are further divided according to the primary type of NAVAID used to provide guidance to the runway. The more common conventional IAP types include Instrument Landing System (ILS) and Very High Frequency Omnidirectional Range (VOR) procedures; Nondirectional Beacon (NDB), and Automatic Direction Finder (ADF) procedures still exist but are less common. Of these, only the ILS procedures provide three-dimensional guidance. Other types of PAs exist but are less common for civilian and commercial uses.

D.5 Airspace Modernization and Performance-Based Navigation

As part of the Next Generation Air Transportation System (NextGen) modernization efforts, the FAA developed PBN roadmaps and strategies beginning in 2003, with implementation of the first PBN procedures in 2005. PBN was introduced to overcome the limitations of conventional navigation procedures that heavily rely on ground-based NAVAIDs for route structure, leading to more precise and efficient operations, a more flexible and cost-effective infrastructure, and increased environmental, financial, and other benefits.

D.5.1 Components of Performance-Based Navigation

PBN uses satellite-based navigation and onboard avionics to define routes based on required performance rather than the type of NAVAID or sensor. This shift enables more precise, flexible, and fuel-efficient operations, reduces reliance on costly ground infrastructure, and supports optimized airspace management to meet growing traffic demands.

RNAV and RNP are the core components of PBN. RNAV uses ground-based and space-based (e.g., GPS) NAVAIDs to define a flight path and for a properly equipped aircraft, can guarantee adherence to the flight path within a specified lateral tolerance, which is usually provided in NM. RNP adds onboard performance monitoring and alerting to RNAV. RNP requires a specific accuracy regarding the path flown and requires the aircraft to continuously monitor its performance and alert the crew if it falls outside the required limits. This capability enhances safety and allows operations in more challenging environments, such as curved approaches or terrain-constrained areas (Honeywell 2019).

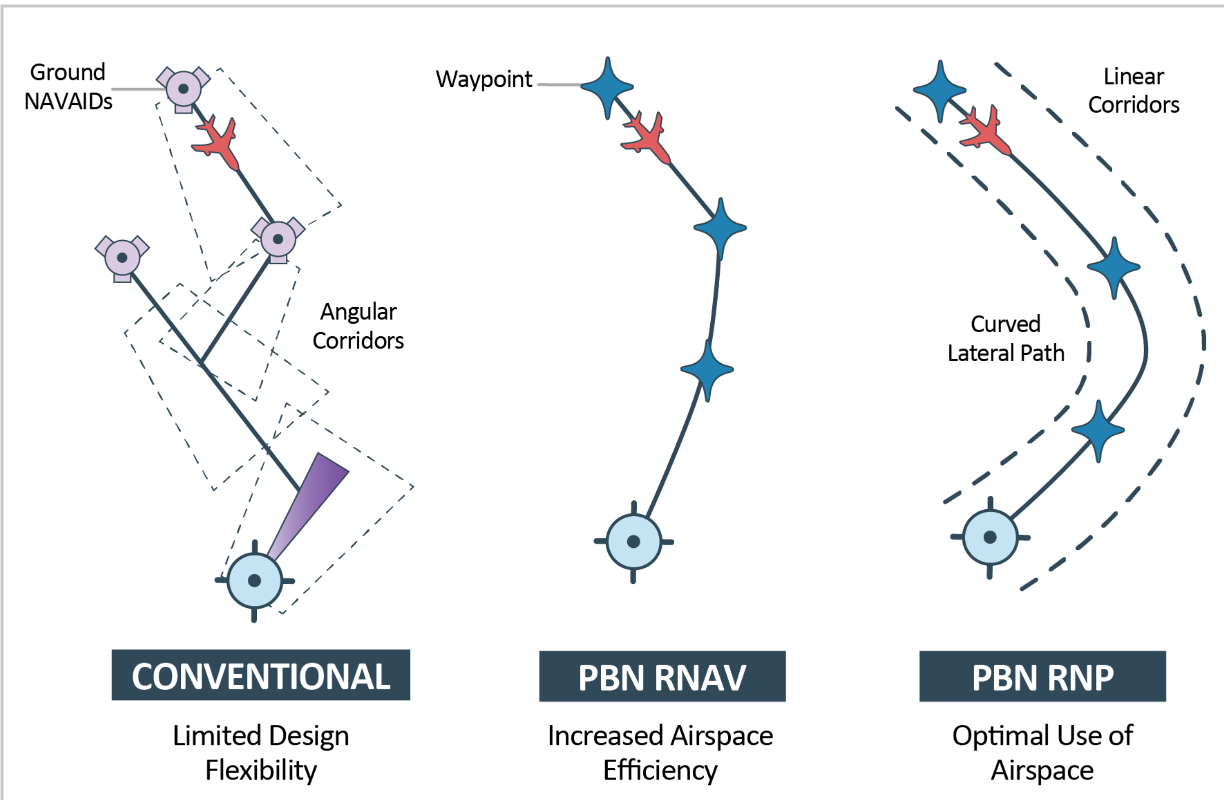
PBN requires three elements: navigation accuracy specifications, the NAVAID infrastructure, and the navigation application/environment (FAA 2025b). The specification defines the requirements for the aircraft and the aircrew to support the use of RNAV and/or RNP procedures within a certain airspace environment. The specification includes procedures, sensors, and performance requirements, including accuracy, integrity, and continuity. The NAVAID infrastructure includes ground-based and space-based NAVAIDs, and the navigation environment identifies the phase of flight and type of airspace the specification and infrastructure apply to (e.g., approach, terminal, or en route). Navigation accuracy requirements vary depending on the navigation environment, with the most stringent requirements typically applied during the approach phase.

D.5.2 Comparing Conventional and Performance-Based Navigation Procedures

Conventional IFPs have been used in the NAS for several decades, providing reliable navigation based on established and familiar ground-based NAVAIDs. The procedures and their infrastructure are widely available and are well known by pilots and air traffic controllers, making their use and implementation easy and providing a consistent navigational basis for those using them. However, as previously mentioned, conventional procedures have drawbacks, most notably those associated with the physical infrastructure required to enable them. Conventional procedure design links a series of NAVAIDs into a path, which limits routes to the physical location of these NAVAIDs and often results in longer flight paths, inefficiencies, and higher operating costs. Additionally, radio frequencies used to support conventional NAVAIDs are subject to line-of-sight issues, which present accessibility and placement issues in challenging terrain and also lead to suboptimal routes.

Exhibit D-4 illustrates the difference between conventional, RNAV, and RNP procedures. Compared to conventional procedures, RNAV and RNP procedures provide greater flexibility and accuracy in route design. The physical infrastructure required for conventional NAVAIDs limits where they can be placed, since they typically require adequate clearance around them to allow for appropriate reception and performance, which can lead to less optimal route and procedure design. Conventional NAVAIDs also require regular maintenance and calibration and, as technology advances, are also affected by hardware obsolescence. GPS-based NAVAIDs do not experience these limitations (Honeywell 2019). **Table D-1** compares several characteristics of conventional and PBN procedures.

Exhibit D-4. Comparison of Conventional Navigation, RNAV, and RNP Procedures



Source: HMMH 2025

Table D-1. Comparison of Conventional and PBN Procedures

Characteristic	Conventional	PBN
Navigation Basis	Procedures are tied directly to the physical location and signal of a specific ground NAVAID.	Based on performance capabilities of onboard equipment, such as required accuracy, integrity, and functionality. Performance is independent of specific ground sensor limitations.
Route Design	Routes are defined by specific radials, courses, or bearings to/from ground stations, often resulting in less efficient and direct paths. Limited to straight-line segments.	Allows for the design of optimal, direct flight paths (including curved paths/RNP AR), reducing distance flown.
Accuracy	Depends on and varies according to the specific NAVAID type and the distance from the NAVAID.	Requires specific accuracy as stated in the procedure to be flown and includes onboard performance monitoring and alerting (RNP). Accuracy requirements must be met 95 percent of the time.
Vertical Guidance	Limited. Most conventional approaches only provide lateral guidance. ILS approaches are the only commonly used approaches with vertical guidance.	Integrated and often continuous. PBN procedures can provide vertical and lateral guidance throughout an approach.
Infrastructure	Reliant on extensive ground-based infrastructure (transmitters, antennas, power, maintenance). Requires periodic maintenance and calibration. Affected by hardware availability.	Primarily reliant on satellite signals (GNSS/GPS) and advanced onboard avionics. Limited need for ground-based infrastructure. Concerns regarding GPS interference.
Terrain/Obstacle Handling	Limited by line-of-sight requirements, which can be problematic for terrain and obstacle avoidance.	No line-of-sight requirements. High precision and accuracy can provide access to areas that may not be accessible with conventional procedures.
Weather	Less access during poor weather due to sensor accuracy and lack of vertical guidance.	Built-in vertical and lateral guidance and accuracy requirements allow for use in more challenging weather conditions and provide greater reliability, accessibility, and safety during those periods.
Operational Efficiency	Less efficient; leads to longer flight times, increased fuel burn, and more pilot-controller communication (e.g., ATC vectors).	Highly efficient; results in shorter flight distances, reduced fuel consumption, improved airspace capacity, and fewer ATC instructions.
System Monitoring	Limited information regarding NAVAID availability provided to aircraft operator. Often limited to binary flags.	RNP systems include onboard performance monitoring and alerting, notifying the crew immediately if navigation performance requirements are not met.

ATC: Air traffic control
GNSS: Global Navigation Satellite System
GPS: Global Positioning System
ILS: Instrument Landing System
NAVAID: Navigational aid
PBN: Performance-Based Navigation
RNP: Required Navigational Performance
RNP AR: Required Navigation Performance with Authorization Required

By enabling more direct and optimized flight paths, PBN reduces overall flight distance, which translates into lower fuel consumption and greenhouse gas emissions. PBN procedures also enable optimized climb and descent profiles (Optimized Profile Climb [OPC] and Optimized Profile Descent [OPD]) that allow aircraft to climb or descend with minimal changes to engine power settings. These profiles are more energy efficient, resulting in greater fuel efficiency, reduced emissions and noise, and lower workloads for pilots and controllers.

The implementation of PBN procedures can reduce noise footprints around airports by concentrating flight paths along predictable corridors and enabling continuous descent operations, which are quieter than traditional step-down approaches. However, concentrated routes may shift noise exposure to specific communities, requiring careful environmental review and stakeholder engagement. Air quality benefits arise from reduced fuel burn, which lowers emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter, improving local and regional air quality.

Because PBN procedures can be designed with greater accuracy and precision, and because advanced on-board equipment is required to fly the procedures, increases in accuracy, repeatability, and consistency can be made in the NAS. PBN procedures allow controllers to assign a predictable, known route to pilots, reducing the communications and workload placed on both pilots and controllers.

D.6 Summary

The use of PBN in the modernization of the NAS represents a critical evolution in aviation operations. Conventional navigation procedures are a key component of safe flight but are constrained by the physical location and limitations of ground-based NAVAIDs, resulting in operational inefficiencies and higher operational costs. PBN addresses these challenges by employing satellite-based navigation and advanced avionics to enable precise, flexible, and performance-driven routing. By using RNAV and RNP specifications, PBN can enhance safety, optimize airspace capacity, and support environmentally sustainable operations by reducing fuel burn and emissions. Implementing PBN does require investment in equipment, avionics, training, and compliance, but its benefits are critical in achieving modernization goals and addressing the limitations and needs associated with a complex airspace system and increasing demand for air transportation.

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