GeoProgress Journal, Vol. 10. i. 1, 2023 – Geoprogress Editions
ISSN 2384-9398, DOI: https://doi.org/10.20373/2384-9398/19

ANALYSIS OF THE IMPLEMENTATION OF THE PERFORMANCE BASED NAVIGATION FOR A MORE EFFICIENT AND SUSTAINABLE AIR TRANSPORT

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Abstract

The aviation sector is a very important industry from economic and social points of view. But the aviation industry significantly contributes to anthropogenic climate changes. In 2008, the aviation industry agreed a global, sector-wide climate action framework. This framework is based on a set of three global goals: short, medium and long-term. The most ambitious climate target is to halve carbon emissions by 2050, compared to 2005 levels. Long term goals could be largely reached with sustainable aviation fuel or new important technology such as electric-engine aircraft. But another important aspect to reach this last goal and to satisfy medium-term goal is the Air Traffic Management optimization.

This paper aims to analyse the environmental and economic benefits of the Performance Based Navigation that can optimize aircraft routes and air transport efficiency all around the world.

Keywords: Aviation, Performance Based Navigation, PBN, RNAV, environmental benefits, sustainability, Air Traffic Management.

1. Introduction

The environmental impact of the aviation industry has been regulated by the International Civil Aviation Organization (ICAO) since the early 1960s following the introduction of the first generation of jet aircraft. Initially, only the noise issues were regulated in Standard and Recommended Practices included in the first edition of the Annex 16 to the Convention on International Civil Aviation adopted in 1971 (called "Aircraft Noise"). In 1981 the Annex 16 comprised also a second volume concerning aircraft engine emissions and it has been retitled "Environmental Protection". Nowadays the Annex 16 includes four volumes:

- Volume 1, Aircraft Noise 7th edition;
- Volume 2, Aircraft Engine Emission, 4th edition;
- Volume 3, Aeroplane CO2 Emissions, 1st edition;
- Volume 4, Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), 1st edition.

The Annex 16 provides a regulation on technical aircraft characteristics that effect on environmental impact. At the same time ICAO publishes a triennial Environmental

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Report, which is the world reference document analysing pollutant and noise emissions of the aviation industry as well as new technology and best practices
[1]. ICAO also provides specific traffic and environmental impact data to the International Energy Agency (IEA).

At European level, the environmental overall impact of the aviation industry and the necessary milestones to achieve the net zero CO_2 emissions by 2050 are analysed by the "Eurocontrol Aviation Outlook 2050" published in 2022.

The air transport contributes to anthropogenic climate change due to pollutants emissions that lead to a net surface warming. Aircraft emissions consist of carbon dioxide (CO_2), nitrogen oxides (NOx), water vapour, soot and sulphate aerosols. Aircraft flying at high altitudes also increase the global cloudiness through the formation of persistent contrails when the atmosphere is supersaturated.

Furthermore, over the past decades the aviation sector grew rapidly: considering the RPK (Revenue Passenger Kilometers) we can notice a significant increase passing from 109 billion km yr^{-1} of 1960 to 8293 billion km yr^{-1} of 2018[2]. The CO_2 emissions in the same period increased from 6.8 to 1034 Tg CO_2 yr^{-1} [3].

The cumulative emissions of global aviation (1940–2018) are 32.6 billion tonnes of CO_2, of which approximately 50% were emitted in the last 20 years. The 2018 CO_2 emissions from air transport represent approximately 2.4% of anthropogenic emissions of CO_2 (including land use change)[4].

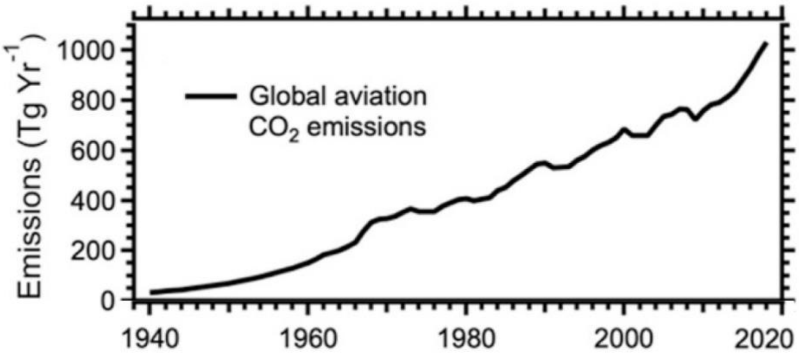

Figure 1: Global aviation CO_2 emissions.
Source: D.S. Lee et al, 2021.

According to De Andreis (2020) "due to Covid-19 pandemic the aviation sector has faced the most critical challenges in its history"[5]. The world passenger air traffic experienced an unprecedented reduction, 2.7 billion passengers less, -60% from the preceding year. The pandemic restrictions caused an economic damage for airlines of

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[1] This paper analysed the *2022 Environmental Report,* International Civil Aviation Organization, Montréal.

[2] Airliners for America (A4A) association, ICAO data.

[3] Le Quéré, C., 76 others, 2018. Global carbon budget 2018. *Earth System Science Data* 10, 2141–2194.

[4] D.S. Lee et al, The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, *Atmospheric Environment*, Volume 244, 2021, 117834, ISSN 1352-2310

[5] De Andreis F., 2020. Strategies of resilience to pandemic storm in the airline industry, *Geopress Journal.*

USD 372 billion loss of gross passenger operating revenues in 2020 compared to 2019 (ICAO, 2022 Environmental Report).

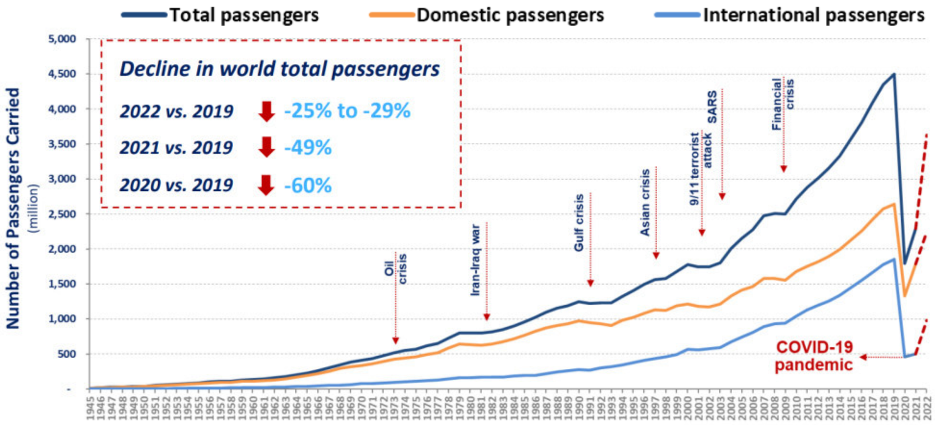
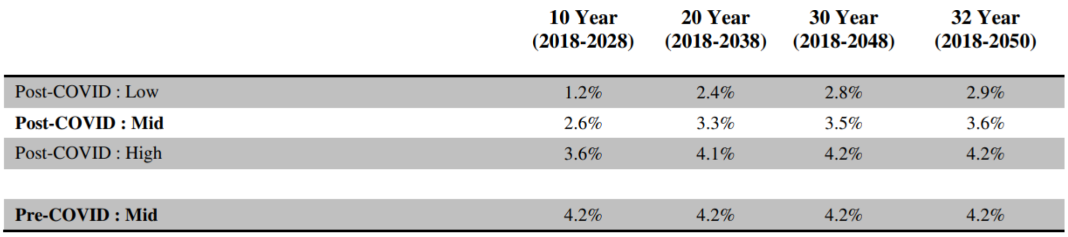


Figure 2: World passenger traffic evolution, 1945–2022.
Source: D.S. ICAO Environmental Report, 2022.

Despite the enormous reduction in the air traffic volume has reduced the greenhouse gas emissions from aviation of about 43% in 2020 (IEA, 2022), this is not sufficient to invert the global warming tendency. Moreover, the air transport traffic is growing up again. The ICAO MDWG-LTF (Multi-Disciplinary Working Group on Long-term Traffic Forecasts) and ICAO Secretariat developed three forecast scenarios on passenger traffic growth following the COVID-19 pandemic crisis. These three scenarios represent the low, mid and high trend forecast. In the intermediate and most probable scenario the RPK (Revenue Passenger-Kilometers) is expected to increase of about 3.3% per year up to 2038.



	10 Year (2018-2028)	20 Year (2018-2038)	30 Year (2018-2048)	32 Year (2018-2050)
Post-COVID : Low	1.2%	2.4%	2.8%	2.9%
Post-COVID : Mid	2.6%	3.3%	3.5%	3.6%
Post-COVID : High	3.6%	4.1%	4.2%	4.2%
Pre-COVID : Mid	4.2%	4.2%	4.2%	4.2%

Figure 3: RPK forecasts scenarios.
Source: ICAO Post-COVID-19 Forecasts Scenarios.

For the ECAC (European Civil Aviation Conference) airspace, Eurocontrol elaborated in April 2022[6] three possible scenarios to evaluate traffic and CO_2 growth (low, base and high scenarios).
Considering the 11.1 million flights in 2019, after the Covid-19 pandemic, the most-likely scenario shows an increase of up to 16 million IFR flights in 2050 (base scenario).

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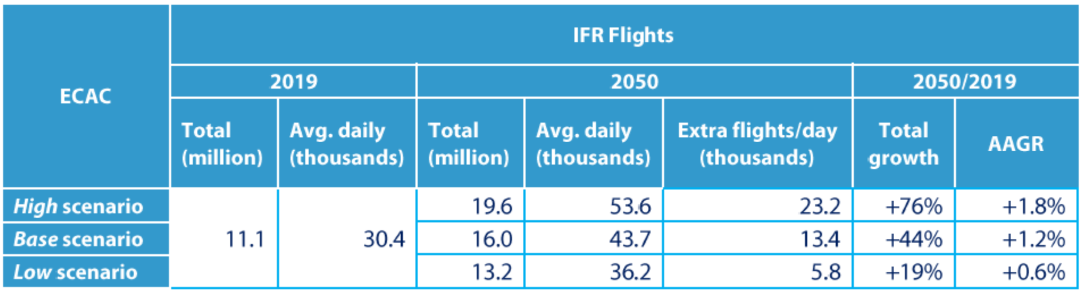
[6] Eurocontrol, 2022, Eurocontrol Aviation Outlook 2050.



ECAC	IFR Flights						
	2019		2050			2050/2019	
	Total (million)	Avg. daily (thousands)	Total (million)	Avg. daily (thousands)	Extra flights/day (thousands)	Total growth	AAGR
High **scenario**	11.1	30.4	19.6	53.6	23.2	+76%	+1.8%
Base **scenario**			16.0	43.7	13.4	+44%	+1.2%
Low **scenario**			13.2	36.2	5.8	+19%	+0.6%

Figure 4: Eurocontrol scenarios of traffic growth.
Source: Eurocontrol Aviation Outlook 2050.

At present and for some considerable time into the future, aviation growth is likely to be largely dependent upon the combustion of kerosene fossil fuel (Jet A-1/A) (OECD, 2012). Every kilogram of JET A-1/A burnt produces 3.16 kg of CO_2 (ICAO Carbon Emissions Calculator Methodology, 2018), 15.14 g of NO_X (Fleming and Ziegler, 2016), 1.231 kg of water vapor (Berrett et al, 2010) and 1,2 g of Sulfur SO_2 (Miller et al., 2010).

According to D.S. Lee et al (2021), fuel usage and hence CO_2 emissions have grown at a lesser rate than RPK. This demonstrates the increased air transport efficiency nowadays due to improved aerodynamical and engine characteristics, larger average aircraft sizes and increased passenger load factor. The air transport efficiency has enhanced by about eight times since 1960.

Therefore, the aviation sector plays a crucial role to achieve the goals of the Paris Agreement, aiming to keep a global temperature rise below 2°C Celsius (compared to pre-industrial levels) and to continue efforts to limit the global temperature growth even further to 1.5° Celsius.

In April 2008, at the 3rd Aviation and Environment Summit, held in Geneve (Switzerland), the aviation industry agreed a global, sector-wide climate action framework. The agreement was signed by airlines associations (ATAG and IATA), airports association (Airport Council International), ANSPs association (CANSO), engine and aircraft manufactures (Airbus, Boeing, Embraer, Bombardier, ICCAIA, Cfm, Pratt & Whitney, GE, Rolls-Royce). The framework is based on a set of three global goals: short, medium and long-term. The short-term goal was set to achieve a 1.5% average annual fuel efficiency improvement from 2009 to 2020 using new aircraft that ensure 20% more fuel efficiency than previous models. This goal is being surpassed with an average improvement of 2% per year. The medium-term goal is set to stabilise net aviation CO_2 emissions at 2020 levels through carbon-neutral growth. Long-term goal aims to reduce net CO_2 emissions to 50% of what they were in 2005 by the 2050.

On this direction, in 2019, the ICAO at its 40th triennial Assembly, adopted the Resolution A40-18 establishing two similar goals: a fuel efficiency improvement of 2% per year and a carbon-neutral growth from 2020 (this last goal was previously established at the 37th session of ICAO Assembly in 2010).

To reach the medium-term goal of a carbon-neutral growth the air transport sector is undertaking a combination of technological, operational and infrastructural enhancement with the first implementation of sustainable aviation fuels and market-based measures.

Most of the operational and infrastructural improvements are the result of the implementation of GNSS (Global Navigation Satellite System) and PBN (Performance Based Navigation), which enhance Air Traffic Management (ATM).

ATM improvements are a key factor to reach the long-term goal as well. Eurocontrol forecasts that to reach a reduction of 40% of net CO_2 emissions in 2050 compared to 2005 levels, aviation industry shall proceed to implement the following actions:

- extensive use of Sustainable aviation fuel (41% of net CO_2 reduction);
- evolutionary and revolutionary fleet renewal (19% of net CO_2 reduction);
- operational and ATM improvements (8% of net CO_2 reduction).

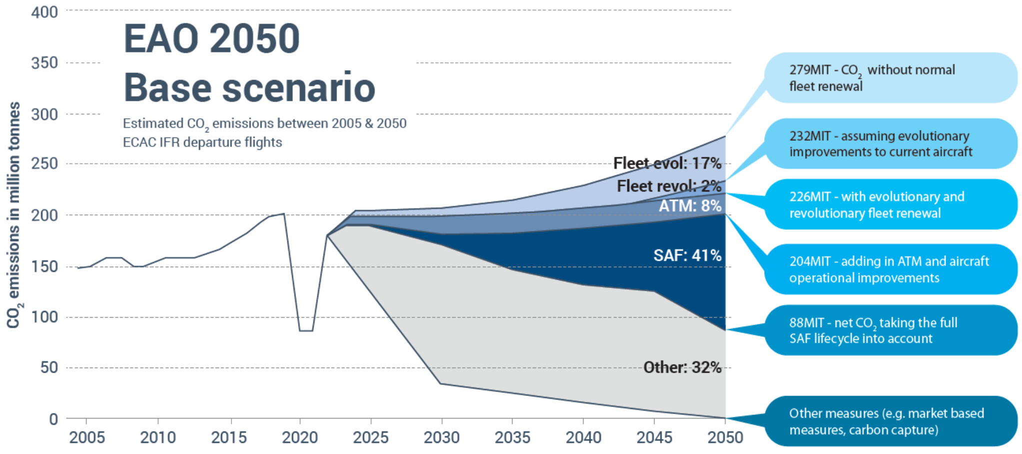


Figure 5: Measures to reach net CO2 emissions.
Source: Eurocontrol Aviation Outlook 2050.

This analysis shows the results in terms of performance efficiency, cost reductions and environmental benefits of the Performance Based Navigation applications.

2. PBN characteristics

The ICAO DOC 9613 is the reference document on Performance Based Navigation (PBN). Furthermore, the ICAO DOC 8168 defines detailed international standard policies that national authorities have to follow to build PBN instrument procedures.

The Performance Based Navigation is the evolution of the Area Navigation (RNAV) concept. According to ICAO definition, the Area Navigation is "a method of navigation which permits aircraft operation on any desired flight path within the coverage of ground or space-based navigation aids (GNSS) or within the limits of the capability of self-contained aids, or a combination of these".

RNAV has been implemented for the first time in USA in the 70s owing to the evolution of computers and their use on onboard aircraft systems.

Navigation data, obtained from onboard navigation systems, are transmitted to a computer called FMC (Flight Management Computer). The FMC processes these data and shows the results to flight crew in a flexible and clear manner. This solution permits to fly on direct routes without the need to overfly radio-aids (as for traditional routes).

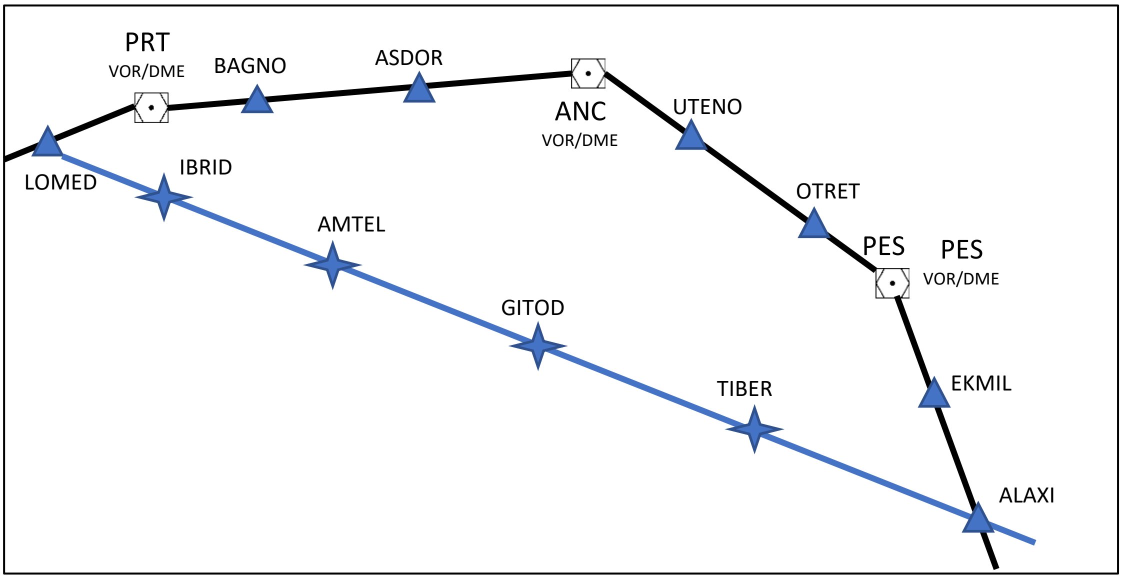


Figure 6: Comparison between a traditional route (in black) and a RNAV route (in blue).
Note: this image is an example and does not represent a real route.
Source: Author's elaboration.

The use of direct routes enhances the airspace efficiency and capacity; it also increases the number of routes and permits a better tactical Air Traffic Management.

An FMS (Flight Management System) onboard the aircraft, automates a wide variety of in-flight tasks through the use of real-time navigation and flight data. This information is elaborated with the support of specific databases: a navigational database and a performance database. The navigation database contains routes, waypoint and other constraints, whereas the performance database stores the specific parameters regarding airplane performance during the various stages of the flight. The computed information is presented in an integrated and efficient manner on specific aircraft displays reducing the pilot's workload. Pilots can interact with the FMS using a specific interface, that is generally called CDU (Command and Display Unit).

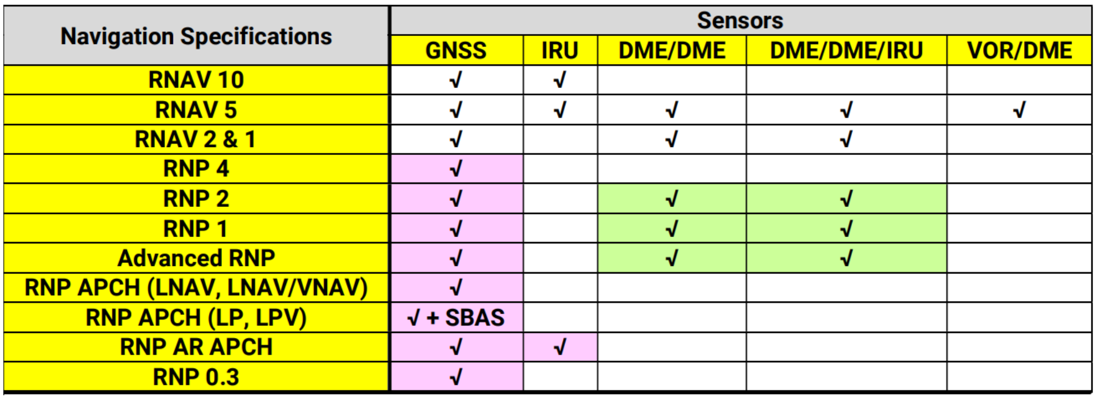
The objective of PBN principles is to standardize RNAV and Required Navigation Performance (RNP) specifications limiting different national interpretations and avoiding the multiplication of distinct navigation specifications across the world. The PBN concept is the evolution of RNAV systems adding further requirements to permit the usage of this systems on critical phases of flight. According to DOC 9613 "Airborne performance requirements are expressed in navigation specifications in terms of accuracy, integrity, continuity and functionality needed for the proposed operation in the context of a particular airspace concept".

RNP specifications include a requirement for on-board performance monitoring and alerting while RNAV specifications do not include this requirement.

The precision of an RNAV or an RNP system is indicated with a number representing the total system error (TSE). TSE is expressed as a deviation in nautical miles from the desired path to be achieved at least for the 95 % of the flight time by the population of aircraft operating within the airspace, route or procedure. PBN ensures predictable and reliable flight path according to detailed navigation specifications.

PBN is not a sensor-specific system and it can rely on different navigation systems (navigation infrastructure) according to airspace concept requirement (defined by DOC 9613). GNSS will become the primary navigation infrastructure of PBN systems. In EU, according to European regulation, the GNSS will be, by 2030, the PBN's main positioning source too. Nevertheless, it is necessary to ensure that a minimum operational network of terrestrial navigation aids remains available for contingency operations and to support normal operations for those aircraft which are either not PBN certified or not GPS equipped.
The PBN can be used for every phase of flight:

- for the departure phase using RNAV2, RNAV1, RNP1 specifications;
- for remote navigation (e.g. oceanic) using RNAV10, RNP4, RNP2 specifications;
- for the enroute phase using RNAV5, RNAV2, RNAV1, RNP2 specifications;
- for the arrival phase using RNAV5, RNAV2, RNAV1, RNP1 specifications;
- for the approach phase with a 2D guidance using RNP APCH (LNAV, LP) specifications;
- for the approach phase with a 3D guidance using RNP APCH (LNAV/VNAV, LPV) specifications;
- for the approach phase of flight implementing curved paths (also on the final segment) and reducing lateral and vertical obstacle clearance using RNP AR (Authorization Required) APCH specification.



Navigation Specifications	Sensors				
	GNSS	IRU	DME/DME	DME/DME/IRU	VOR/DME
RNAV 10	√	√			
RNAV 5	√	√	√	√	√
RNAV 2 & 1	√		√	√	
RNP 4	√				
RNP 2	√		√	√	
RNP 1	√		√	√	
Advanced RNP	√		√	√	
RNP APCH (LNAV, LNAV/VNAV)	√				
RNP APCH (LP, LPV)	√ + SBAS				
RNP AR APCH	√	√			
RNP 0.3	√				

Legend:

- This table is based on the Navigation Specifications in the ICAO Doc 9613 PBN Manual
- A tick with pink background means a sensor mandatory
- A tick wit green background means a sensor used subject to ANSP approval, appropriate infrastructure and aircraft capability;
- A tick with no background means a sensor optional (one or more – choice of operator).

Figure 7: sensors required for each navigation specification in Europe.
Source: Eurocontrol ERNIP PART 1, 2022.

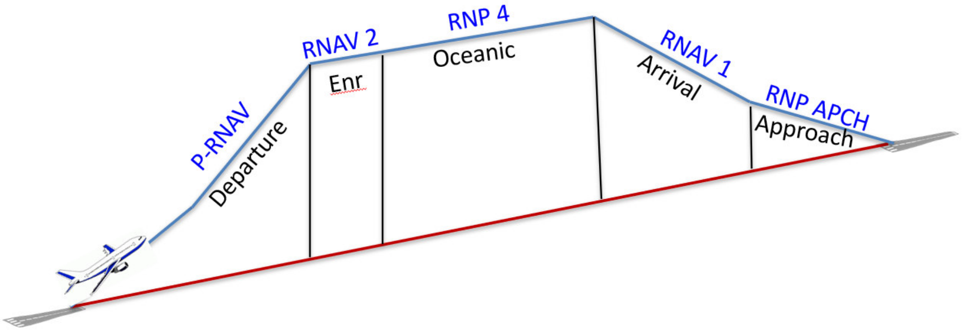


Figure 8: example of multiple navigation specifications used for a single flight.
Source: Author's elaboration.

To optimize aircraft trajectories *fly-by* waypoints can be used instead of *fly-over* waypoint.

According to DOC 8168:

"Fly-by waypoint: a waypoint which requires turn anticipation to allow tangential interception of the next segment of a route or procedure;

Flyover waypoint: a waypoint at which a turn is initiated in order to join the next segment of a route or procedure."

For fly-by transitions, the ideal paths vary with aircraft bank angle and airspeed so no repeatable and predictable trajectories are specified.

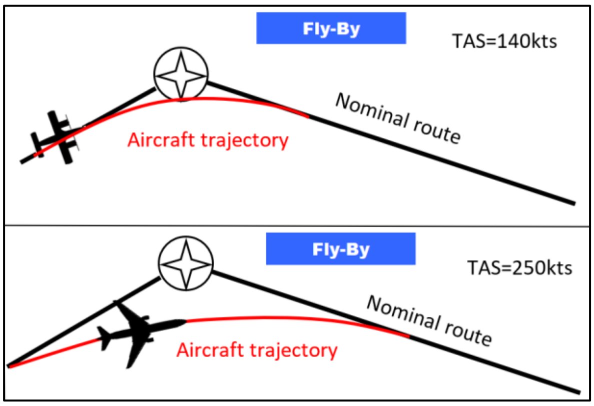


Figure 9: example of routes computed by the FMS on two different aircraft with different speeds.
Source: Author's elaboration.

For curved path Radius to Fix (RF) or Fixed Radius Transition (FRT) can be used.

The RF trajectory is used in terminal and approach phases of flight. The circular path is determined with a constant radius built around a defined turn centre. The path terminates over a specific waypoint. The FMC permits to follow the circular nominal route with the same accuracy as in the straight-line segments.

The FRT trajectory is used during enroute phase of flight. The turning radius of FRT can assume only two possible values: 22.5 NM for airways above FL 195 and 15 NM for airways at or below FL 195. The more reliable and precise navigation permitted by PBN (also for curved paths) allow to build closely spaced parallel routes improving airspace capacity.

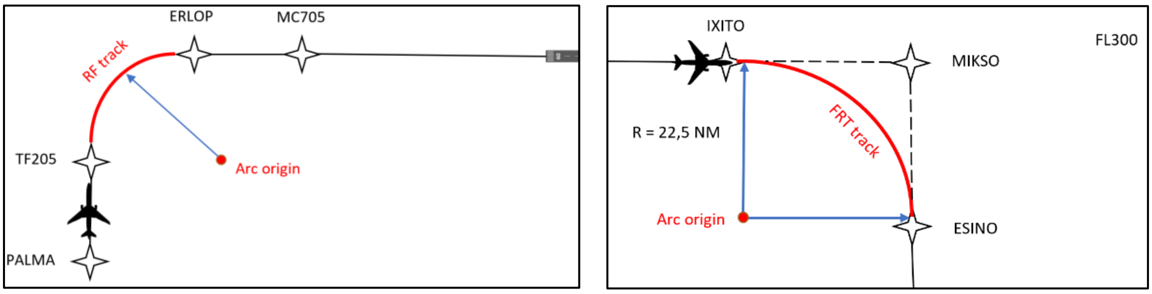


Figure 10: examples of Radius to Fix arc (on the left) and Fixed Radius Transition (on the right).
Source: Author's elaboration.

3. Results of PBN applications in terms of operational and environmental benefits

3.1 PBN operational and environmental benefits

Performance Based Navigation enables a series of operational benefits as outlined below:

- the possibility to fly straighter and shorten flight tracks;
- increased airspaces capacity and trajectory optimizations;
- increased efficiency of vertical navigation profiles implementing Optimized Profile Descent (OPD), Continuous Descent Operations (CDO) and Continuous Climb Operations (CCO);
- reduction of the need of radar vectors due to more predictable routes permitting the aircraft to fly more efficient pre-calculated tracks;
- reduction of the possibility of diversions and missed approaches owing to a more resilience navigation infrastructure less dependent to ground equipment;
- reduction of the likelihood of in-flight holding;
- reduction of contingency fuel required (lowering aircraft weight and fuel consumption) owing to system predictability and reliability.

These operational improvements lead to the following environmental benefits:

- significant reductions of fuel consumptions and consequent reduction of CO_2 and pollutants emissions such as carbon monoxide, NO_x, sulphate aerosols and soot;
- reduction of flight path distances and increase in trajectory efficiency on vertical profile: continuous descent applications permit to execute descents maintaining idle thrust and reducing noise emissions;
- noise concentration in non-sensitive area owing to greater navigation accuracy and the increase in route predictability that reduce the need of radar vectors and permit the concentration of departure and arrival routes on less populated areas;
- reduced aerodynamic noise from optimum drag profiles.

The benefits of PBN procedures are analysed in the following paragraphs examining the applications for the enroute phase, for the approach and climb phases and to reduce noise emissions. Significant case-studies are also presented.

3.2 PBN operational and environmental benefits for the enroute phase of flight

Two of the most important projects in the world that aim to modernize air traffic infrastructure and operations are the SES (Single European Sky) project and NextGen. Both projects are based on extensive use of GNSS and PBN technology.

NextGen is a US project and, as described by the Federal Aviation Administration[7], "it aims to increase the safety, efficiency, capacity, predictability and resiliency of American aviation". Through research and collaboration, NextGen contributes to define new standards thanks to a series of interlinked programs, portfolios, systems, policies, and procedures that are fundamentally changing aviation communications, navigation and surveillance. Within its scopes there are airport infrastructure improvements, new air traffic management technologies and procedures, and environmental, safety and security-related enhancements. The NextGen project is being undertaken by the US Federal Aviation Administration (FAA) and aims to simplify US ATM by rolling out PBN and Automatic Dependent Surveillance-Broadcast (ADS-B) that will replace radar technology, as well as collaborative air traffic management technologies.

The SES is a European project: the main objective is to reform Air Traffic Management (ATM) in Europe in order to cope with sustained air traffic growth and operations under the safest, most cost- and flight-efficient and environmentally friendly conditions. This implies de-fragmenting the European airspace, reducing delays, increasing safety standards and flight efficiency to reduce the aviation environmental footprint and costs[8]. SESAR (Single European Sky ATM Research), an institutionalised European public-private partnership, was created to reach, through research and development, the goals and the delivery of the Single European Sky. The SES legislative framework consists of four Basic Regulations (N° 549/2004, 550/2004, 551/2004 and 552/2004) and more than 20 Implementing Rules and Community Specifications adopted by the European Commission. The Basic Regulations cover the provision of air navigation services (ANS), the organisation and use of airspace and the interoperability of the European Air Traffic Management Network (EATMN) revised by the Regulation (EC) n° 1070/2009.

One of the projects of SES is Free Route Airspace (FRA). FRA is an airspace where operators can plan aircraft routes in a freely way between a defined entry point and a defined exit point without the obligation to follow a published ATS route because of PBN technology.

FRA is a new airspace concept that redefine the structure of upper airspace improving flight efficiency. In this way airspace capacity is improved and fuel consumption and emissions are reduced.

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[7] Federal Aviation Administration, NextGen program. https://www.faa.gov/nextgen.

[8] European Commission, Single European Sky. https://transport.ec.europa.eu/transport-modes/air/single-european-sky_en

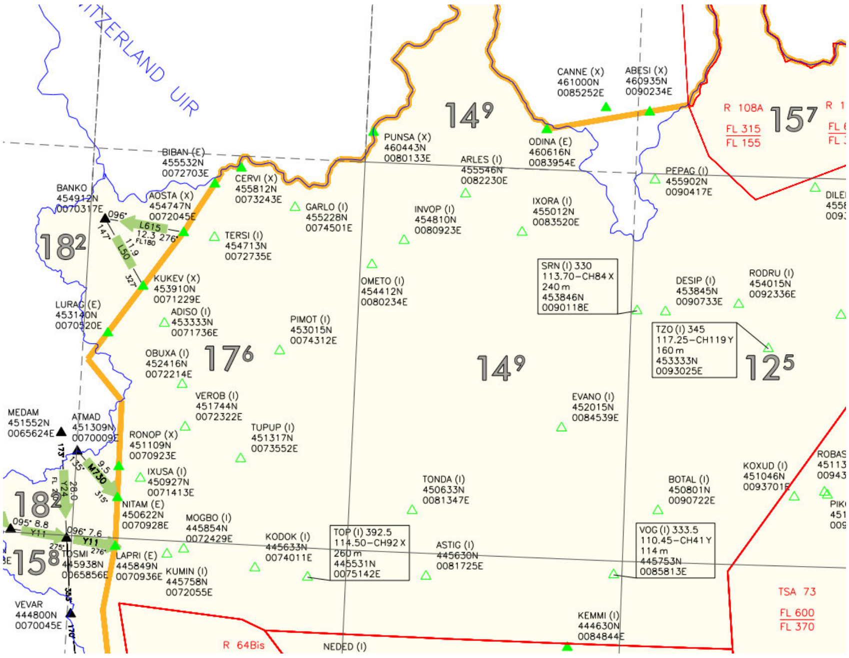

Figure 11: A portion of the Italian Free Route Airspace above FL305.
Source: ENAV, AIP Italia.

The ideal and most efficient route coincide with a great circle track. The route extension (difference between route flown by aircraft and great circle track), as calculated by Eurocontrol, reduced from 3.58% in December 2007 to 2.00% in December 2021.

Nowadays the actual saving induced by the FRA (according to Eurocontrol data) is:

- 500 nautical miles of trajectories reduction;
- 3000 tonnes of fuel;
- 9500 tonnes of CO_2;
- 3 million euros.

The Free Route Airspace will be progressively implemented over the ECAC (European Civil Aviation Conference) zone as shown in figure 12.

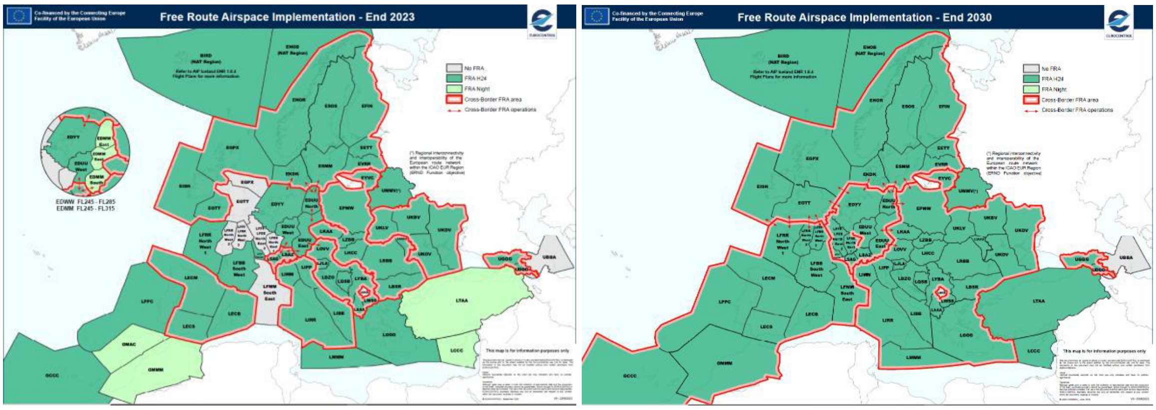

Figure 12: FRA implementation, comparison at the end of 2023 (left picture) with the situation expected at the end of 2030 (right picture).
Source: Eurocontrol, June 2022.

According to Eurocontrol data and studies, "once fully implemented at European level, the FRA will allow the following savings, compared with the current situation:

- 1 billion nautical miles of trajectories reduction;
- 6 million tonnes of fuel;
- 20 million fewer CO_2 tonnes;
- 5 billion euros in fuel costs savings".

3.3 PBN operational and environmental benefits for approach and climb phases of flight

In terminal area, PBN enables more direct routes, the possibility of curved trajectory (also for the final phase of flight on RNP AR approaches), the reduction of approach minima (MDA/H or DA/H), the reduction of the probability of missed approaches, the optimization of climb and descent phases owing to vertical navigation (VNAV).

The trajectory optimization and the more predictable tracks reduce the need of radar vectoring during the instrument approach phase, lowering ATC workload.

According to ICAO definitions[9] "Continuous Climb and Descent Operations (CCOs and CDOs) are aircraft operating techniques enabled by airspace design, instrument procedure design and facilitated by air traffic control (ATC). CCO and CDO allow aircraft to follow a flexible, optimum flight path that delivers major environmental and economic benefits - reduced fuel burn, gaseous emissions, noise and fuel costs - without any adverse effect on safety".

CCO and CDO operations allow aircraft to descend or climb continuously: departing aircraft applying CCO maintain optimum climb engine thrust and climb speeds until reaching their cruising levels whereas arriving aircraft applying CDO descent at the minimum engine thrust from top of descent and in a low drag configuration stabilizing on final approach. The employment of these techniques reduces intermediate level-offs and results in a reduction of fuel consumption owing to a flight time increase at higher or cruising levels, hence significantly reducing fuel burn and lowering emissions and fuel costs as confirmed (concerning CDO) by Errico A., Di Vito V. (2017).

According to Eurocontrol data, after an ECAC-wide study on CCO and CDO analysis[10], the complete deployment of CCO and CDO in Europe will have the following economic and environmental impacts:

- 340,000 tonnes of fuel saved;
- about 150,000 million in in fuel costs savings;
- 1 million fewer CO_2 tonnes.

The study concluded that for CCO, 94% of flights in ECAC currently fly CCO to FL (Flight Level) 100 while 74% fly a full CCO to Top of Climb. For CDO, 41% of flights fly CDO from FL75 (the top of the noise CDO) while only 24% fly a CDO from Top of Descent (ToD – the top of the fuel CDO). Another key point of the study is that the potential fuel saving benefits of CDO are about ten times more than those from CCO.

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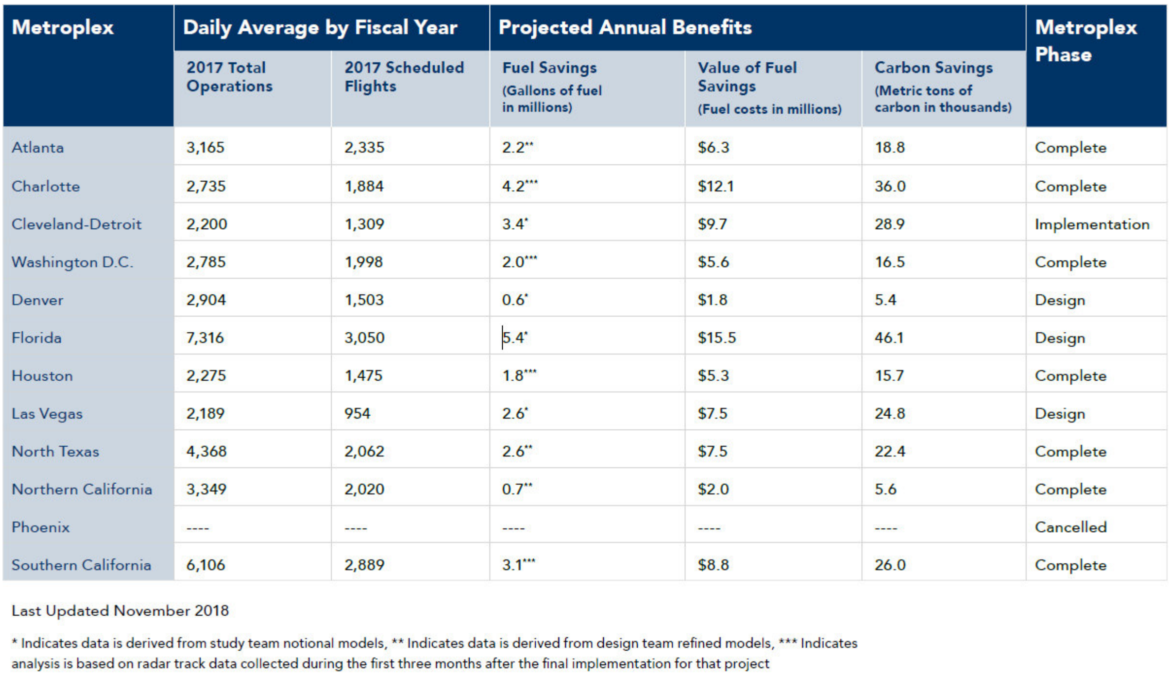
[9] ICAO Doc 9993 and ICAO Doc 9931

[10] Eurocontrol website, Continuous climb and descent operations.

As a demonstration of fuel consumption reduction and environmental benefits in the approach and climb phases of flight, the table below shows the CANSO data[11] in the US Metroplex operations following the PBN implementation.



Metroplex	Daily Average by Fiscal Year		Projected Annual Benefits			Metroplex Phase
	2017 Total Operations	2017 Scheduled Flights	Fuel Savings (Gallons of fuel in millions)	Value of Fuel Savings (Fuel costs in millions)	Carbon Savings (Metric tons of carbon in thousands)	
Atlanta	3,165	2,335	2.2**	$6.3	18.8	Complete
Charlotte	2,735	1,884	4.2***	$12.1	36.0	Complete
Cleveland-Detroit	2,200	1,309	3.4*	$9.7	28.9	Implementation
Washington D.C.	2,785	1,998	2.0***	$5.6	16.5	Complete
Denver	2,904	1,503	0.6*	$1.8	5.4	Design
Florida	7,316	3,050	5.4*	$15.5	46.1	Design
Houston	2,275	1,475	1.8***	$5.3	15.7	Complete
Las Vegas	2,189	954	2.6*	$7.5	24.8	Design
North Texas	4,368	2,062	2.6**	$7.5	22.4	Complete
Northern California	3,349	2,020	0.7**	$2.0	5.6	Complete
Phoenix	----	----	----	----	----	Cancelled
Southern California	6,106	2,889	3.1***	$8.8	26.0	Complete

Last Updated November 2018

* Indicates data is derived from study team notional models, ** Indicates data is derived from design team refined models, *** Indicates analysis is based on radar track data collected during the first three months after the final implementation for that project

Figure 13: Metroplex airports data of savings following PBN implementation. Source: CANSO, 2020.

3.4 PBN implementation as a noise mitigation technique

PBN benefits are not limited to the reduction of fuel consumption, pollutants and greenhouse gasses emitted in the atmosphere but this navigation technique can be efficiently used to mitigate noise pollution.

The possibility to create precise and flexible routes with an increased predictability enables to create tracks that avoid as much as possible noise sensitive areas during departure and landing phases. Topographical features, such as rivers, highways or agricultural areas, can be used when available.

Traditional routes and ATC vectors have not the same predictability as PBN/RNAV routes with aircraft not passing over the same reporting point at the same altitude on regular basis: this causes a “dispersion” of flights.

With PBN implementation more aircraft may fly over a series of waypoints and the correlated areas on the ground, with the resultant “concentration” of engine and airframe noise. The noise concentration derived from PBN can be a valuable noise mitigation technique if used appropriately to concentrate operations over non-populated and less noise-sensitive zones.

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[11] CANSO, 2020. Use of Performance Based Navigation (PBN) for Noise Management.

Figure 14: RNP AR approaches at Ottawa airport able to avoid two noise-sensitive areas (circled in red).
Source: CANSO.

In areas where densely populated zones are very close from an airport a hybrid situation can provide more benefits, such as in Lester B. Pearson International Airport (figure 15). In this way radar vectors could disperse noise in the initial climb whereas the PBN-concentrated portion of the routes, (e.g. the start of an RNAV SID transition), can be placed such that the concentration occurs away from densely populated areas (CANSO, 2020).
The concentration aspect of PBN routes can be an effective mitigation technique to airplane noise. This instrument procedures should be designed and published to keep aircraft trajectories over non-residential zones.

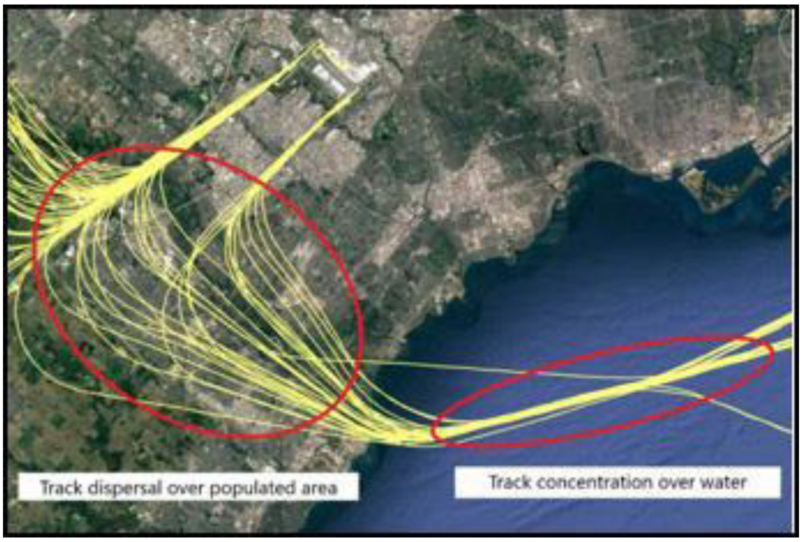


Figure 15: Example of hybrid approach in Lester B. Pearson International Airport (Toronto).
Source: NAVCANADA.

3.5 Case study: San Francisco RNP to GLS approach runway 19R

A specific study (Boeing, 2016) was conducted in San Francisco airport in August 2016 to improve airport efficiency with new approach procedures. In the demonstration took part San Francisco Airport, Boeing, FAA and two aircraft (Boeing 737-900ERs) of Delta Air Lines and United Airlines. According to the study, one procedure that features a much shorter turn to final approach, reduces the distance flown by twenty nautical miles and time spent in the air, cuts emissions by up to 771 kg per approach, avoids nearby Oakland Airspace, and improves community noise exposure for several densely populated East Bay communities. The revised RNP to GLS (GBAS Landing System) procedures to runway 19R was a Continuous Descent Operations with a near-continuous idle-thrust descent for landing. The objective of this new approach trajectory was also to minimise the use of speed brakes (avoiding to increase aerodynamic drag) and aiming to increase flight efficiency and to reduce fuel consumptions compared to vectored routes.

The estimated population exposed by the noise produced from this type of procedure consisted of 47,300 people versus the 329,600 people involved in a short vector or 296,500 in a long vector to final. Therefore, this demonstrates the benefits of PBN procedures in terms of noise alleviations.

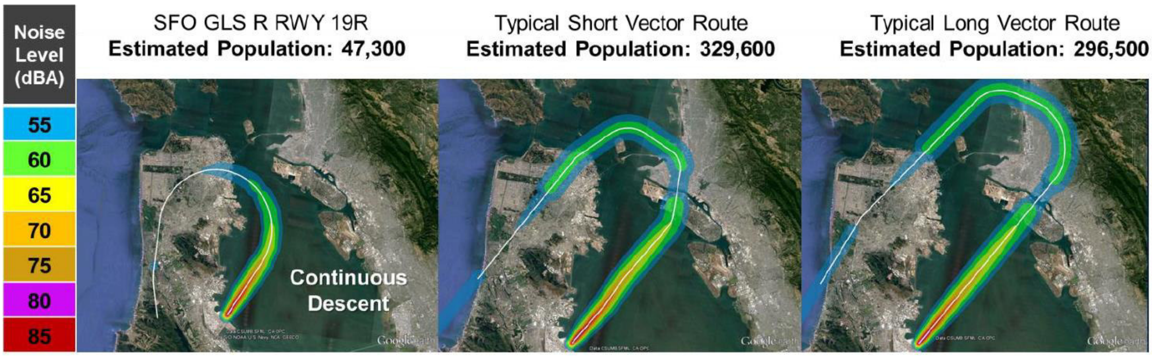


Figure 16: Comparison of noise exposure in San Francisco between a RNP approach and two kinds of radar vectors.
Source: Boeing.

Moreover, the PBN approach procedures ensure a greater flexibility in vertical guidance compared to ground-based instrument approaches (such as the ILS-Instrument Landing System). In fact, in a PBN approach the descent angle can be adjusted according to local requirements (such as obstacles or noise attenuation) and it can be modified between different procedures.

As an example, the GLS final approach segment of runway 28R in San Francisco was modified to 3.25° compared to the typical 3° glideslope of the ILS. Boeing has demonstrated that a higher descent angle in the final segment of the GLS procedure has reduced the fuel burnt over the standard ILS (Boeing, 2016).

The study has estimated a fuel burnt reduction of the Boeing 737-900ERs of up to 50 lbs per approach for the RNP to GLS procedure with a 3.25º final glideslope. As a result, this decreases the CO_2 emissions of 158 lbs. The data is to be considered as an example because these values can vary with aircraft type, meteorological conditions,

aircraft weight, throttle movements. However, it was registered an improvement compared to the 30 lbs of fuel savings obtained from an analytical estimate.
The figure 17 compares the two kinds of approaches (conventional vs. PBN) conducted in San Francisco with the same airplane model.
The graph on top links altitudes with distances from the runway threshold while the bottom graph compares the rotational speed of the engine fan ("N1 #1 CMD"") versus the distance from the runway threshold. N1 is proportional to engine thrust setting and effects fuel flow; the fuel flow integrated over the approach defines the fuel burnt.

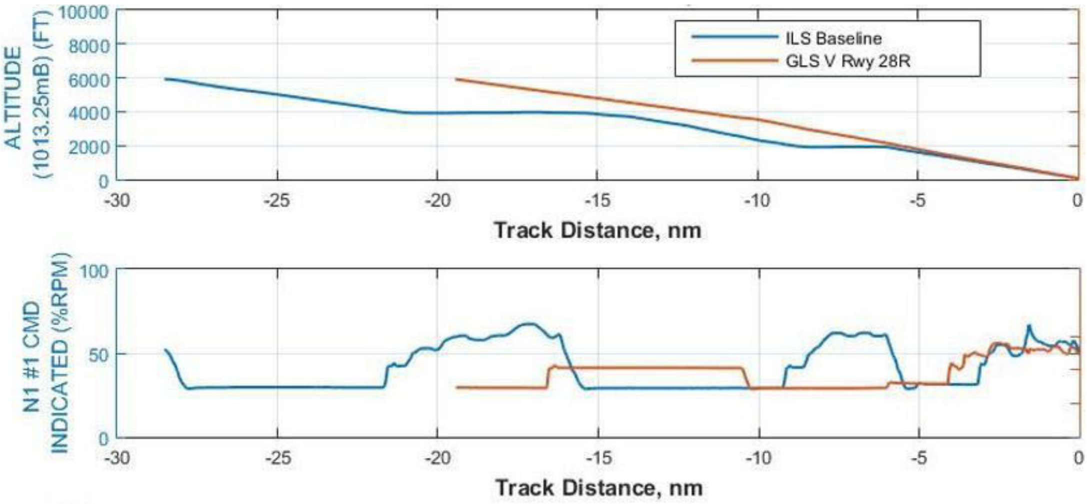


Figure 17: Altitude and Engine Throttle setting comparisons for the approaches (GLS and ILS) to runway 28R in San Francisco.
Source: Boeing.

The absence of levelled segments is evident in the GLS approach as well as the lower throttle setting required. As a result, there is a reduction of fuel flow, fuel burnt, CO_2 and noise emissions.

3.6 Case study: London Stansted airport

Another case-study of London Stansted airport is reported below demonstrating the noise reduction benefits of PBN procedures applied in departure tracks as a result of track concentration due to greater navigation accuracy and the increase in route predictability.
London Stansted Airport has implemented RNP with Radius to Fix routes for departure in order to meet the regulatory requirement laid down by EASA and also improving the efficiency of flight operations and the environmental impact.
An initial trial of RNP (RF) procedures took place in 2013 with a single airline participant and with the support of NATS (the UK enroute ANSP) and CAA (the national aviation authority) in order to prove the benefits of utilising PBN at Stansted. The procedure was evaluated with the commitment of the people living in the nearby area. During the consultation phase of 2015, 71% of respondents were supportive about the SIDs modification. This led to approve the procedures as permanent. Compared to conventional departures, the new PBN standard departures decrease by 85% the number of people overflown with a reduction of two thirds of the area involved by the noise pollution (CANSO, 2020).

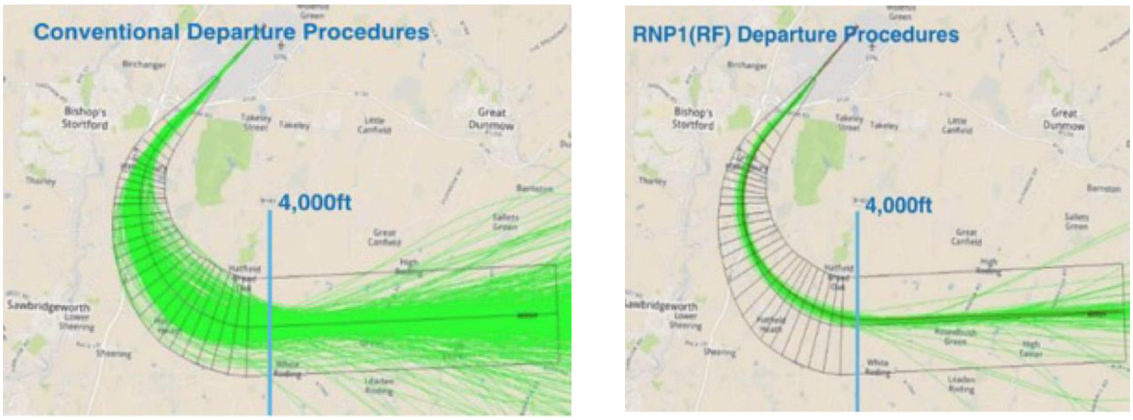
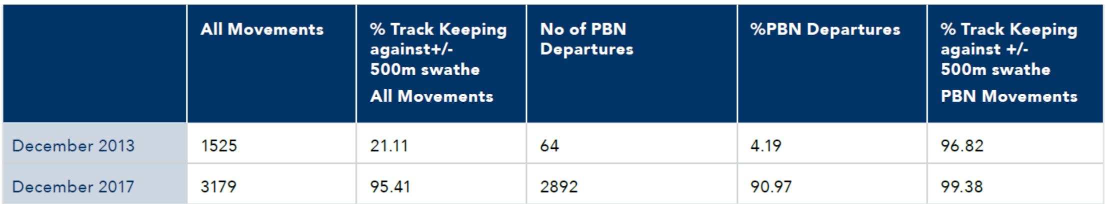


Figure 18: Comparison of areas overflown by conventional departures (width of approximately 1500m) and RNP departures (width of approximately 500m) before 4000 feet.
Source: NATS.

The table below (figure 19) shows the difference in track accuracy between the instrument departure procedures really flown in December 2013 (95.81% of non-PBN procedures) and instrument procedures flown in December 2017 (90.97% of PBN procedures): in December 2017 (PBN environment) 95.41% of departing aircraft maintained their routes in the symmetrically area of ±500 metres width disposed about the nominal flight track compared to the 21.11% of December 2013.



	All Movements	% Track Keeping against+/- 500m swathe All Movements	No of PBN Departures	%PBN Departures	% Track Keeping against +/- 500m swathe PBN Movements
December 2013	1525	21.11	64	4.19	96.82
December 2017	3179	95.41	2892	90.97	99.38

Figure 19: Comparison in track accuracy between PBN and non-PBN departure routes in London Stansted airport.
Source: CANSO.

This demonstrates as PBN procedures improve the resilience of the aviation industry reducing the environmental impact in city airports.

4. Conclusions

Data reported on this analysis clearly shows that PBN implementation not only has operational benefits but also has a significant contribution on improve aviation environmental impact.

PBN applications can effectively reduce fuel consumption, pollutants emissions and greenhouse gasses emissions in the atmosphere thanks to trajectories optimization and system reliability. This is evident considering actual and future data of Free Route Airspace project and CANSO data of fuel and CO_2 savings on Metroplex airports.

PBN ensures operational and infrastructural improvements that are the basis of ATM optimization. This optimization has a key role to reduce environmental aviation impact and to reach the goal of halving CO_2 emissions by 2050. In particular according to Eurocontrol studies on future air traffic growth, ATM optimization will contribute to reduce of 8% the carbon emissions: considering the base scenario it will be necessary a reduction of 22 million tonnes of CO_2 emitted in atmosphere only in ECAC airspace. Forecast data on this analysis shows that we will be able to reach a reduction of 21 million CO_2 tonnes emitted in the atmosphere from the benefits of Free Route Airspace complete implementation (20 million CO_2 tonnes saved) and from a complete employment of Continuous Climb and Descent Operations (1 million CO_2 tonnes saved). Aggregated data of fuel savings following a complete PBN implementation and optimization of airport routes (arrival and departure tracks) are not available but in the author's opinion the 1 million CO_2 reduction can be obtained taking into account the data available from CANSO in the US airports.

The case-studies reported on this analysis also demonstrate that PBN routes can effectively reduce the impact of noise pollution on populated areas that surround airports reducing in a significant way the number of people overflown by aircraft due to the concentration of this routes over non-populated areas. City airports can benefit from a complete PBN routes implementation resulting in a better air quality and in a reduction of noise emission due to air transport. In particular, the reduction of air pollutants is the result of track reduction, continuous climb applications and descend optimization (as demonstrated by CANSO study on Metroplex airports). The noise level reduction is permitted by the greater accuracy and the increase in route predictability that reduce the need of radar vectors and permit the concentration of departure and arrival routes on less populated areas. This conclusion is evident observing the data available and results of San Francisco airport and London Stansted airport after the introduction of RNP approaches or RNP departures.

To conclude, Performance Based Navigation is a real opportunity for air transport that can improve resilience, efficiency and the environmental impact of the aviation industry. This navigation system is also the basis of other major improvements and ATM optimization projects in order to reach important goals to combat climate change.

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