

**EVALUATION OF NEW ENROUTE PERFORMANCE MEASURES FOR AIR
NAVIGATION SERVICE PROVIDERS.**

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**EVALUATION OF NEW ENROUTE PERFORMANCE MEASURES FOR AIR
NAVIGATION SERVICE PROVIDERS.**

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When you want something, all the universe conspires in helping you to achieve it.

Paulo Coelho

To my parents,

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SUMMARY

In a context of steady growth of air traffic world wide, Air Navigation Service Providers must meet increasing demand and report on the quality of their performance. This research presents the design and evaluation of novel performance metrics: the relevance of ATC set of standard routes, the lateral deviation and difference in length and duration between airlines filed flight plans, actual trajectories and wind optimal routes. The proposed metrics are predicated on the necessity for the metrics to be robust, easy to compute and applicable to several different Air Traffic Management Systems, eg. Europe vs USA.

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Air Traffic Management

As in any industry, global comparisons and benchmarking including data analysis can help drive performance and identify best practices in Air Traffic Management (ATM). Over the years, various groups have tried to analyze the inefficiency that can be addressed by improvement in the ATM system. In Europe, an initial set of performance indicators was developed in 1996 [**POMERET97**], using data available in EUROCONTROL, the European Organization for the Safety of Air Navigation, an intergovernmental organization made up of 39 Member States and the European Community. Similarly, in the United States, one of the goals of the Federal Aviation Administration (FAA) is to support the safe and efficient movement of air transportation. Historically, throughput and delay have been used to measure the effectiveness of the ATM system and its impact on the operating efficiency of its customers. While delay is an adequate measure of operational effectiveness in some instances, it does not present a complete picture of the many aspects of performance that determine the quality and level of service the users receive. Recognizing this, the FAA is working to improve the approach and metrics it uses to assess its performance and the level of service that domestic and oceanic airspace users receive [**BOLCZAK19979**]. The context makes the identification and introduction of new performance measures difficult, because they must be simple enough to be apprehended by many members of the aviation community, robust to be independent from one system to another, uniform and consistent enough that they enable objective comparisons from year to year and across continents.

1.2 Objectives of the thesis

The objective of this thesis is to propose candidate performance metrics based on flight plans filed before take-off and understand the existing disparities between each submitted flight plan. Studies on actual trajectories have already been conducted. But rather than exploiting the trajectories post-flight, the study not only focuses how the decisions are taken before take-off, but also how the flight plans are chosen. Previous studies were conducted by Eurocontrol on horizontal flight efficiency indicators [Euroc2016] and provided a measure of the average en route additional distance with respect to the great circle distance. Eurocontrol and FAA agree that the metrics based on achieved distance do not account for weather conditions in the choice of a flight plan [kettunen2005flight]. The development of an indicator based on the "optimum" trajectory from the point of view of an airline is one other innovation of this paper.

1.3 Thesis outline

Four metrics will be developed in this thesis. The first metric is the evaluation of ATC set of preferred routes based on the analysis on an airline set of flight plans. The three others metrics focus on the comparison in lateral deviation, time and length of analyzed trajectories (filed or actually flown) with a new en route ideal trajectory: the wind optimal route based on the airline's point of view.

CHAPTER 2

BACKGROUND THEORY

2.1 Key performance Area, Key performance Indicators and Performance metrics

It is first imperative to make sure that one understands the distinction between the definitions of Key performance Area (KPA), Key performance Indicators (KPI) and Performance metrics.

- KPAs attempt to capture the fundamental areas of performance that can be evaluated in any system. They are a way of categorizing performance subjects related to high level ambitions and expectations.
- KPIs are used to measure the KPAs. An indicator is a high level concept which describes how the FAA and EUROCONTROL will meet their long term strategic goals. KPI is a quantitative expression of actual progress in achieving performance objectives i.e. current/past performance and future expected performance. Indicators are not often directly measured.
- A metric is the quantification of a performance indicator in a particular domain including both the method of calculation and the data source used.

One indicator may have more than one metric. In ATM, given the differences between operations in the various phases of flight, there may be more than one way to quantify a given concept. Considering the structure and size of ATM in the worldwide, the task of defining or choosing metrics proves to be complex. Historically, frameworks and methodology have been studied to assist the rigorous development and consistency of performance metrics [BRADFORD2003], [Mondoloni2005], [ISO1998], [Williams2004] and [ASANTE2012].

2.2 US/Europe Harmonized Key Performance Indicators

The US and Europe are two areas in the world where air traffic has increased over the past decades. For a number of operational, geopolitical and climatic reasons, Air Traffic Flow Management (ATFM) techniques have evolved differently in the US and in Europe.

2.2.1 Air Traffic Flow Management (ATFM) and Air Traffic Control (ATC)

Although the total surface of continental airspace is similar for Europe and the US, there is a key difference between the way the two systems, illustrated on Figure 2.1, are operated. Europe is fragmented in many individual sovereign states. European study area comprises 37 Air Navigation Service Providers (ANSPs) of various geographical areas. Together they operate 62 en-route centers and 16 stand-alone Approach Control (APP) units (total: 78 facilities). The US study area (CONUS) has 20 en-route centers supplemented by 26 stand-alone Terminal Radar Approach Control (TRACON) units (total: 46 facilities), operated by one single service provider. Since 2004, the Single European Sky (SES) initiative of the European Union aims at reducing this fragmentation, increasing the capacity and improving the efficiency and interoperability of the European ATM system.

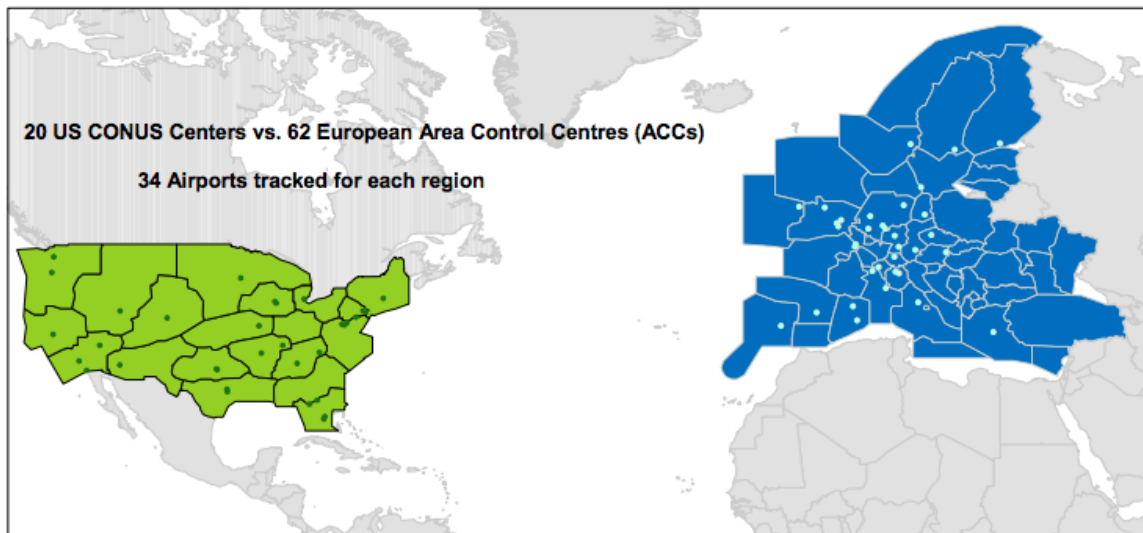


Figure 2.1: Air Traffic Management organization of the United States and Europe.

2.2.2 Airspace design

There is also a difference regarding airspace configurations to accommodate military and civil coordinations and operations in the two systems. Occasionally, to ensure safety of the other airspace users, some airspace are restricted and segregated for exclusive use of military trainings and national security, constraining the civil users to make detours around these areas. Number and locations of the special use of airspace (SUA) vary in time and space within the respective ATM systems. The number of SUA is greater in Europe than in the US as illustrated on Figure 2.2. Quite of them are located in the core area of Europe affecting the flow of civil air traffic whereas most of them in the US are located on the coastlines allowing for less constrained transcontinental connections.

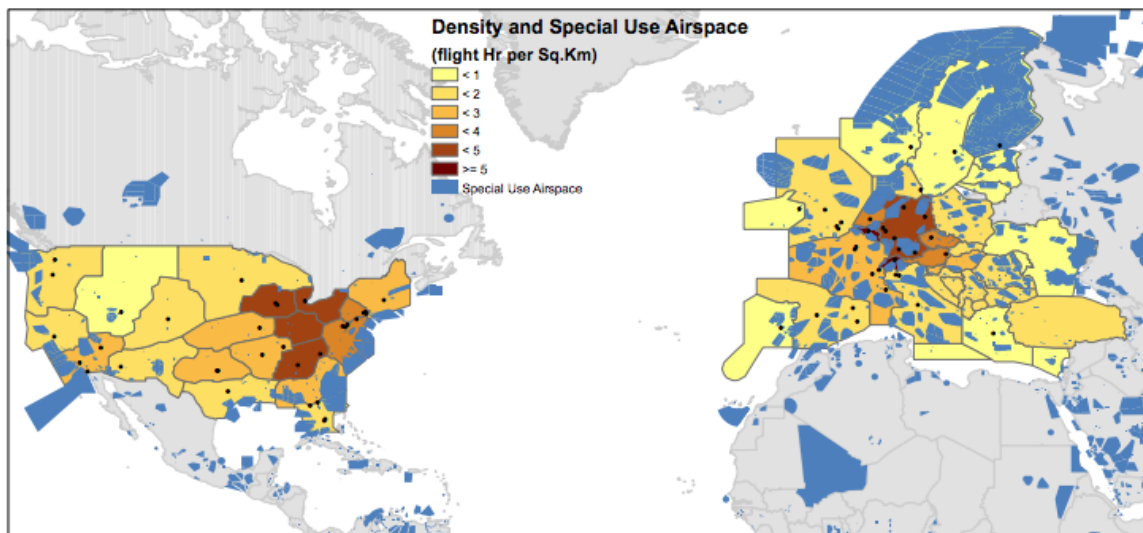


Figure 2.2: Comparison of Special Use Airspace (SUA) between the US and Europe.

2.2.3 Traffic characteristics

Air traffic growth showed notable decoupling in 2004 when Europe traffic continued to growth whereas it started to decline in the US: whereas the European traffic grew by 15.5% between 2000 and 2015, the US one declined by -13.8% during the same period illustrated on Figure 2.3, upper left corner. Regarding air traffic density, both European and the US

systems show irregular air traffic density evolutions between their different states illustrated on Figure 2.3, upper right corner. Average flight length also differs from one state to another in both systems but for both of them, most of the Instrument Flight Rules (IFR) traffic is due to traffic within its respective region. In the US this share is 83.9% compared to 78.4% in Europe summarized on Figure 2.3, bottom left corner. When all IFR flights including overflights are taken into account, the average flight length in Europe is 575 NM compared to 524 NM in the US. Seasonality factors differ between the US and Europe: whereas weekly traffic profiles in Europe and the US are similar (lowest level of traffic during weekends), the seasonal variation is higher in Europe. Compared to average, traffic in Europe shows a clear peak during the summer months (about 15% higher) whereas in the US the seasonal variation is more moderate. A notable difference between the two systems is the share of general aviation which accounts for 22% and 3.7% of total traffic in 2015, respectively, detailed in Figure 2.3, bottom right corner.

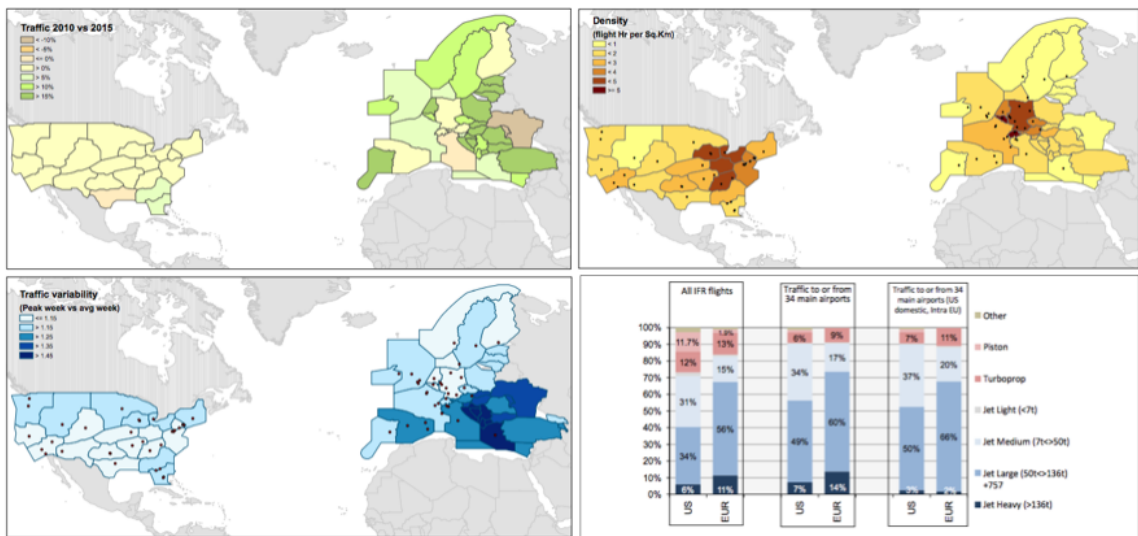


Figure 2.3: Comparison of the US and Europe traffic characteristics: Evolution of IFR traffic in the US and in Europe (2015 vs. 2010), Air Traffic density in the US and in Europe (2015), Seasonal traffic variability in the US and in Europe (2015) and comparison by physical aircraft class (2015).

Since 2003, the two organizations responsible for coordinating ATM system planning, development, and operations in the United States (the FAA) and in Europe (EUROCON-

TROL) have been publishing reports to compare the performances of the two systems [PCR2003], [PCR2009], [ODONI2010], [PCR2012], [PCR2013], [PCR2016]. The International Civil Aviation Organization (ICAO), the FAA, EUROCONTROL and the Civil Air Navigation Services Organization (CANSO) have been working together to develop harmonized KPIs that can be used for international benchmarking. These are the KPAs of Capacity, Efficiency, Predictability, and Environmental Sustainability listed in the top table of *Table 2.1*.

Table 2.1: US/Europe Harmonized Key Performance Indicators. The KPIs in the table are associated with the ICAO KPAs defined in ICAO GANP [GANP2016].

Key Performance Area	Key Performance Indicator
Capacity	Declared Airport Capacity
	Maximum Airport Throughput
Efficiency	Airline-Reported Delay Against Schedule
	Airline-Reported Attributable Delay
	En-route and Airport ATM-Reported Attributable Delay
	Taxi-Out Additional Time
	Horizontal En-Route Flight Efficiency (flight plan and actual)
	Additional Time in Terminal Airspace
Predictability	Taxi-In Additional Time
	Airline-Reported Arrival and Departure Punctuality
	Capacity Variability
	Phase of Flight Time Variability

2.3 Current indicators of the en-route flight efficiency and opportunities for improvement

Depending on the way traffic is managed and distributed along the various phases of flight (airborne vs. ground), ATM has a different impact on airspace users (time, fuel burn, costs), the utilization of capacity (en-route and airport), and the environment (emissions). In order to optimize the overall air traffic network, gate-to-gate ATM efficiency can be analyzed for the different phases of flight. The purpose is to identify the component of the system that offers the potential to improve flight efficiency as well as the group responsible for implementing improvements. Various elements impact efficiency depending on the

phase of flight. For instance, en-route efficiency is mostly impacted by weather conditions, airspace design and restrictions, airspace capacity and ATC capacity. This thesis focuses on the KPA of efficiency and the en route phase of flight defined in details in the next two paragraphs.

2.3.1 Introduction of an ideal flight for the KPA Efficiency

Efficiency measures the difference between actual time/distance and an unimpeded reference time/distance [PCR2016]. While each phase may be measured against an ideal benchmark [KNORR2011], [CANSO2013], this ideal may represent a single flight that may not be feasible in the full network system. However, the total ATM system operational performance may be measured against this ideal in order to identify areas of potential improvement and collaboration among stakeholders within the ATM system. Furthermore, the definition of an ideal flight depends on the perspective adopted. For the airlines, this ideal would be the flight that minimizes the cost of the overall operation trade-off between time and fuel. For ANSPs, capacity efficiency and safety are the main drivers when defining an ideal flight.

2.3.2 En-route part definition

Most of the inefficiencies that occur within the last 100 NM of flight called terminal efficiencies are mostly related to congestion leading to airborne holding patterns, metering and sequencing of arrivals. The efficiency defined for the en-route part tends to avoid the airport influence and the terminal maneuvering areas (TMA) by considering a specific portion of the flight from gate to gate. This en-route efficiency is mainly driven by ATC routing, route utilization and en-route design. Historically, various definitions of the en-route part have been suggested. The en-route definition and ring reference around the airports is an arbitrary choice, as any other distance would be, as there is no harmonized definition for TMA horizontal limits [fuller2004enhanced]. For this work, the en route phase of a flight

is defined as that segment of flight from the termination point of a departure procedure (when leaving the 40 NM circle area around the departure airport) to the origination point of an arrival procedure (when entering the 100 NM circle area around the arrival airport) [CANSOKPI2015].

2.3.3 Current indicators of the en-route flight efficiency

Previous studies were conducted by EUROCONTROL and the FAA on horizontal en-route flight efficiency indicators [PRR2015Eurocontrol],[PCR2016]. To enable consistent comparisons between different city pairs and areas, the first KPI they developed measures the length of actual flight trajectories as additional distance with respect to an ideal flight, which is called the achieved distance. The achieved distance is an apportion of the great circle distance (GCD) between the two reference circles of 40 NM at the departure area and 100 NM at the arrival area. The GCD is the shortest distance between the two airports, flown in that reference airspace. In an ideal (unrealistic and unachievable) situation where there is no congestion and each aircraft would be alone in the system, the horizontal flight efficiency indicator would be equal to zero. The ideal used here only considers the horizontal component of a flight that is, in general, of higher economic and environmental importance and excludes the vertical (altitude) component.

Another comparison in length was introduced between the analyzed en-route trajectory and the most direct course that is the GCD between the exit point of the departure terminal area and the entry of the arrival terminal area. The direct route is generally not aligned with the great circle (GC) linking the two airports. Whereas the difference between the GC linking the two airports and the direct course is more concerned with the location of the TMA entry points, the comparison between the actual flown route and the direct distance focuses on the actual flight plan.

The different routes mentioned for the horizontal en-route flight efficiency indicator are illustrated on Figure 2.4.

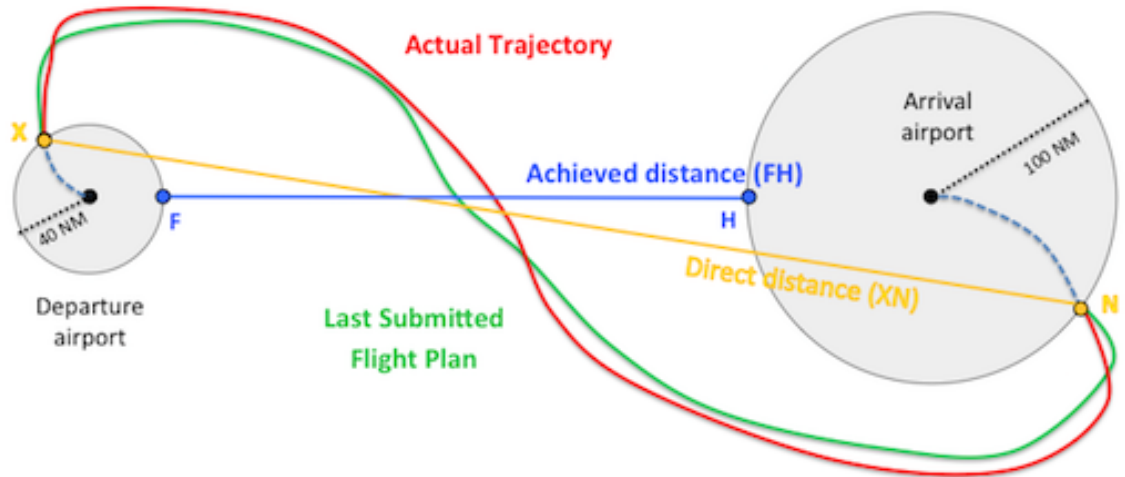


Figure 2.4: Representation of the Achieved Distance (FH), Direct Distance (XN), Actual Trajectory (in red) and Last Submitted Flight Plan by an airline outside the first 40 NM in the departure area and outside the last 100 nautical miles of the terminal area (in green) [calvonev].

The second KPI commonly used for en route efficiency developed by CANSO [CANSOKPI2015] does not study the actual trajectory but compares the last filed flight plan and the benchmark achieved distance. The advantage of this measure is that the effect of winds, thunderstorms, and other operational constraints such as special use airspace, are contained in the flight plan.

ATC current studies on the indicators focus on taking the vertical navigation efficiency into account and better separate en route vs terminal area performance. Studies have recently been conducted to improve the performance indicator of en route efficiency.

2.3.4 Caveats to the en-route flight efficiency indicators

When used at the strategic level, the KPI clearly points to areas where track distance increases or decreases over time. However, there are three main caveats to this distance-based approach that does not necessarily correspond to the optimum trajectory since it does not take into consideration the vertical component, external factors and the operator's perspective.

First, this ideal trajectory based on the achieved distance is defined with a level flight at an ideal cruise altitude. Although the current KPI is based on the horizontal flight efficiency, the trajectory processing should also include some of the vertical components and whether the ideal cruise altitude is maintained during the flight. This last one may be difficult to follow for many external factors including aircraft weight, winds effects and weathers conditions.

Second, there may be very legitimate reasons why direct flight is not used. The current indicator takes a single flight perspective as it relates actual performance to the great circle distance, which is an ideal, unachievable. From a system point of view, safety and capacity require flow separation that has consequently a negative impact on flight efficiency. The goal is not to achieve this ideal target of direct routing for all flights at anytime but an acceptable level of flight efficiency, which balances safety and capacity requirements [PCR2009]. Aircraft are separated for safety reasons or may fly farther distances to avoid severe weather or active Special Use Airspace (SUA). EUROCONTROL and FAA agree that the metrics based on achieved distance do not account for external parameters such as weather conditions, SUA or congestion in the choice of a flight plan [kettunen2005flight].

Third, it is acknowledged that the distance-based flight efficiency indicators developed so far only serve as proxies for fuel efficiency as the most fuel efficient route depends on winds. The direct flight becomes a less useful indicator over longer distances where airlines will prefer wind optimal routes. For these cases, a more sophisticated approach based on wind optimal routes or times or other considerations such as operator business priorities would be required. The development of an indicator based on the "optimum" trajectory from the point of view of an airline will be an additional novelty developed in this study.

2.4 Required Criteria when introducing new KPIs and metrics

ATM system evolves in time and space and restrictions are lifted. Comparing user request-based performance metric from year to year may not yield a consistent basis for compar-

ison. In order to assess user request and operational changes, current metrics should be constantly reassessed and reevaluated and additional metrics should be introduced. This thesis aims at evaluating the en-route efficiency exclusively in the US and Europe. There are two approaches to do so: update existing ones defined in Section 2.3 or introduce new performance metrics. New metrics should exhibit certain characteristics to be valuable and practical:

- Well defined by being **measurable** or able to be determined from other measurements, **clear defined** with its definition and boundaries, **related to a KPA** by indicating progress toward a performance area (between the main KPAs of efficiency, capacity and predictability), **useful** by answering specific questions and needs about the performance.
- Universal by being applicable and used by both systems in Europe and the US to enable consistent comparisons between city pairs and different areas.
- Robust from one year to the next. Changing indicators or metrics over time disables trend analyses and transatlantic comparisons if not adopted simultaneously.

CHAPTER 3

AVAILABLE DATA AND TECHNICAL TOOLS

3.1 Available Data

The KPIs and metrics introduced in this thesis will be applied to the US airspace since the data was given by the FAA and an American airline. Statistics are computed over 7 key city pairs selected over a set of 28 city pairs in the United States.

3.1.1 Airline flight plans (F)

This study relies on 2,652 flight plans on file at take-off given by an American airline. These flight plans are not necessarily the cost-efficient flight plans that the airline would have chosen. They are the result of two processes: the initial choice of a route made at the Operations Center according to numerous parameters, followed by the negotiations with Air Traffic Control (ATC). These flight plans are not always flown by the aircraft nether because of unforeseen events (high traffic volume, pilots' decisions or weather conditions [**cheungsensitivity**]) compelling ATC or the pilots to modify what was planned. The period covered ranges from August 15th, 2014 to September 18th, 2014. This set is a considered as a set of routes ($F \in \mathbb{T}$) since the time information is only available for the first and the last waypoints that are not part of the en route trajectory.

3.1.2 ATC Preferred Routes (PR)

To balance effort with capacity while avoiding congestion, the FAA created many tools different set of pre-defined routes and re-routing sets: the Preferred Routes, Playbook Routes and the Coded Departure Routes (CDRs), issued as either required, recommended, or "FYI". ATC preferred routes are preferred by the FAA and the normal, everyday routes

ATC would like operators to file. They were developed to increase system efficiency and capacity by having balanced traffic flows among high-density airports. The set of PR updated every 56 days can be downloaded online on the FAA preferred route database [FAA database]. The set of PR downloaded covers the period 01/05/2016 to 01/05/2017, recorded as navajds/jet routes is illustrated on Figure 3.1 in boldface lines for the key city pairs studied. This set is a set of routes ($PR \in \mathbb{T}$).

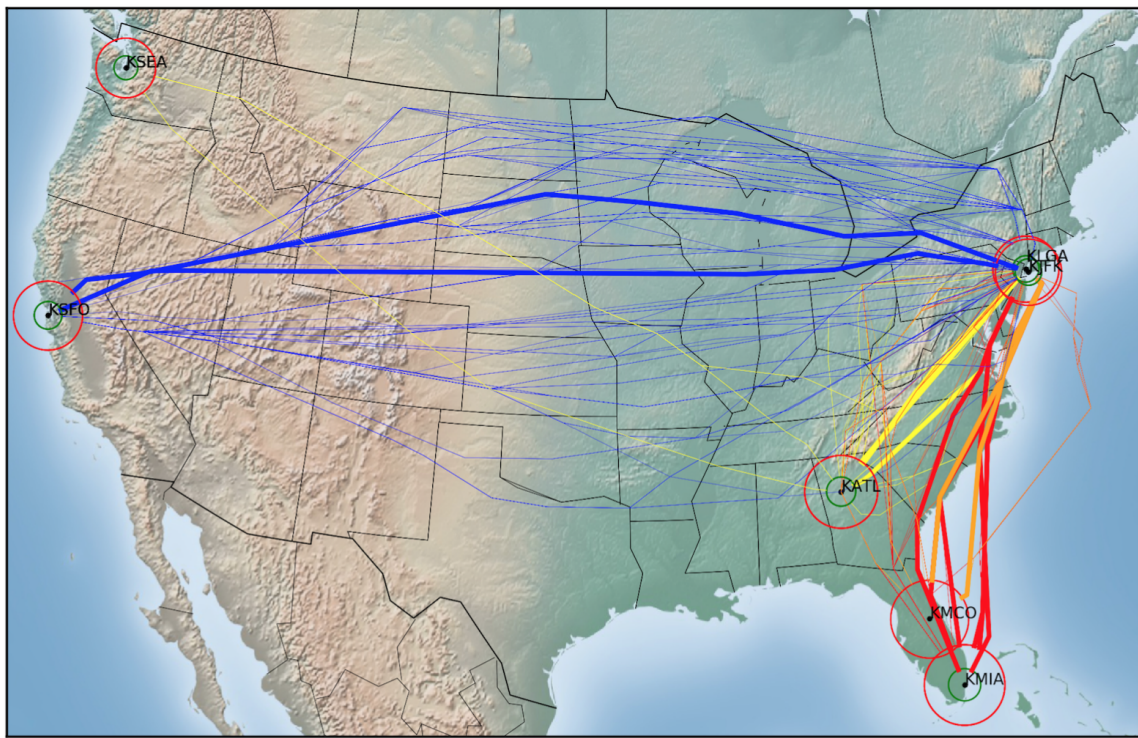


Figure 3.1: Illustration of the sets of preferred routes (in boldface lines) and the Coded Departure Routes (in thin lines) developed by ATC for the key city pairs studied in this thesis. The green circle represent the 40 first NM around the departure airport and red circle the last 100 NM around arrival airport.

3.1.3 ATC CDRs (*CDR*)

Coded Departure Routes (CDRs) are a combination of coded air traffic routings and refined coordination procedures, designed to reduce the amount of information that needs to be exchanged between ATC and flight crews. CDRs are typically used at high capacity airports and during inclement weather to make communication between ATC and flight crews more

efficient. The set of CDRs updated every 56 days can be downloaded online on the FAA preferred route database [**FAA database**]. The set of PR downloaded also covers the period 01/05/2016 to 01/05/2017 and is illustrated on Figure 3.1 in thin lines. This set is a set of routes ($CDR \in \mathbb{T}$).

3.1.4 ETMS Data (A)

The Enhanced Traffic Management System (ETMS) stores all the information gathered by the FAA from aircraft flying in the US airspace. The data stored about each flight includes flight plan information for segments actually flown from January 1, 2013 until August 1, 2014 and for the same period covered by the airline flight plans: from August 15th, 2014 to September 18th, 2014. This set is a set of flights ($A \in \mathbb{F}$).

3.1.5 Weather Data

Weather data is available from the National Oceanic and Atmospheric Administration (NOAA) [**meteoweb**]. Every 6 hours beginning at midnight everyday, NOAA broadcasts a new weather forecast. The forecast is built by the North American Mesoscale Forecast System (NAM). NAM forecasts include a dozen volumetric variables, such as winds aloft and radar reflectivity over different time horizons. The data was downloaded for the period from March 2014 until August 2014.

3.1.6 Airline set of main routes (A_R)

A_R is a set of the main routes used by an American airline for 28 city pairs across the US airspace. This set, comprised of the airline's preferred routes, ATC preferred routes, ATC CDRs, Center preferred routes or Playbook routes, has been computed from 2006 to 2014 by this airline. All the main routes A_R of twelve city pairs are represented in Figure 3.2. The main routes are clustered to better analyze the main paths used by an aircraft. Instead of using a k-means algorithm that regroups the trajectories together around their centroid, a

derivate algorithm using the medoid is selected. Each cluster is represented by its medoid, which is the most representative sample of the cluster. Hence, the algorithm enables the conservation of actual aeronautical way points used in the flight plans. The dataset is re-grouped in 5 clusters at the most.

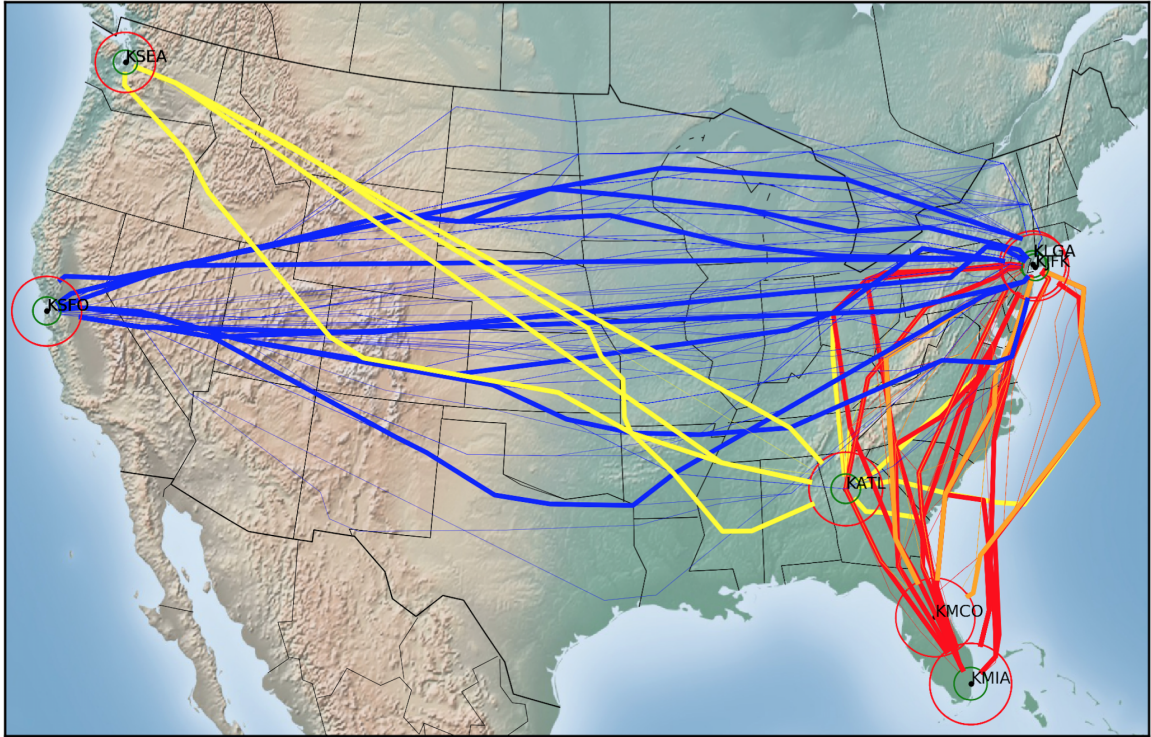


Figure 3.2: Illustration of the main routes (in thin lines) used by an airline for the key city pairs studied in this thesis and the medoids of their clusters (in boldface lines). The green circle represent the 40 first NM around the departure airport and red circle the last 100 NM around arrival airport.

3.2 Mathematical definitions

Let \mathbb{F} be the space of flights, a flight is defined as a finite series of $\mathbb{R}^3 \times \mathbb{R}$. Each element (point or waypoint) of \mathbb{F} represents a position and a time. Let \mathbb{T} be the space of trajectories, a route or a trajectory is a serie of \mathbb{R}^3 . The restriction of a flight to its geometrical representation is a trajectory. For the purpose of notation, the notion of flights is sometimes

confused with trajectories. Besides, only the en route part of a flight is studied. Consequently a flight is always restricted to the en route part between the last point at 40NM from departure ($D40$) and first point at 100NM to arrival ($A100$). Let f be a flight, the en route length of f is L_f and its en route time is ERT_f .

The horizontal area a_{r_1, r_2} between two trajectories $r_1, r_2 \in \mathbb{T}$ is defined to determine lateral proximity. The first step is to remove every loop from the two trajectories. This arbitrary choice is made so that the area computation does not take congestion factors into consideration. Then, the area between trajectories is computed as the sum of the areas of the polygons between each intersection.

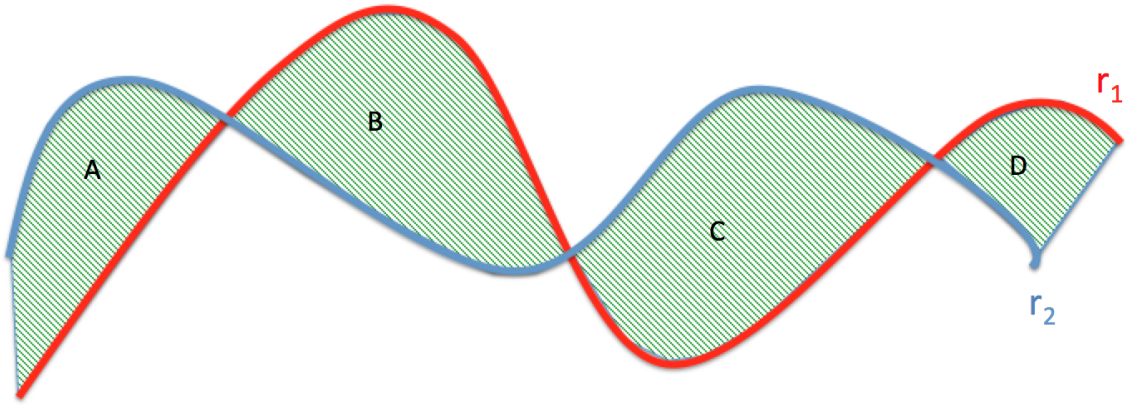


Figure 3.3: Area a_{r_1, r_2} between r_1 and r_2 as the sum of the polygons areas A,B,C,D

In this study, not only individual flights or routes are studied but also entire set of routes or flights. Consequently, different definitions must be made. First, Let $R \in \mathbb{T}^n$ be a set of routes r . The area a_s^R between a route s and the set R is defined as the minimum of the areas $a_{s,r}$ between s and each route r of R in Eq.3.1. The corresponding closest route is c_s^R defined in Eq.3.2.

$$a_s^R = \min_{\forall r \in R} a_{s,r} \quad (3.1)$$

$$c_s^R = \underset{\forall r \in R}{\operatorname{argmin}} a_{s,r} \quad (3.2)$$

The deviation $d_{s,r}$ of a route s from a route r is defined in Eq.3.3 as the area $a_{s,r}$ divided by the length L_r of the en route part of r . This notion can be extended to a set. The deviation d_s^R of a route s from a set R is the area a_s^R divided by the length $L_{c_s^R}$ of the closest route in the set as defined in Eq.3.4.

$$d_{s,r} = \frac{a_{s,r}}{L_r} \quad (3.3)$$

$$d_s^R = \frac{a_s^R}{L_{c_s^R}} \quad (3.4)$$

To overcome the variation in the route lengths and enable possible comparisons between different set of routes, a normalization is applied. This normalization consists in reshaping the deviations like if all the routes r have the same length: 1000 NM. Normalized deviations are defined in Eq. (3.9) and (3.10).

$$D_{s,r} = \frac{1000}{L_r} \times d_{s,r} = \frac{1000 \times a_{s,r}}{L_r^2} \quad (3.5)$$

$$D_s^R = \frac{1000}{L_{c_s^R}} \times d_s^R = \frac{1000 \times a_s^R}{L_{c_s^R}^2} \quad (3.6)$$

With all these definitions, the average lateral deviation $\langle D_S^R \rangle$ of a set of routes R upon a set of routes $S \in \mathbb{T}^n$ and the average lateral deviation $\langle D_{S,r} \rangle$ of a routes r upon a set of routes S can be defined as the average deviation of routes s from the set of routes R .

$$D_{s,r} = \frac{1000}{L_r} \times d_{s,r} = \frac{1000 \times a_{s,r}}{L_r^2} \quad (3.7)$$

$$D_s^R = \frac{1000}{L_{c_s^R}} \times d_s^R = \frac{1000 \times a_s^R}{L_{c_s^R}^2} \quad (3.8)$$

The En Route Length Efficiency (ERLE) and the En Route Time Difference (ERTD) of a route s from a route r are defined in Eq.?? and ?? as the difference of the en route length between s and r divided by the en route length of r multiplied by 100 and the difference of the en route time between s and r , respectively.

$$D_{s,r} = \frac{1000}{L_r} \times d_{s,r} = \frac{1000 \times a_{s,r}}{L_r^2} \quad (3.9)$$

$$D_s^R = \frac{1000}{L_{c_s^R}} \times d_s^R = \frac{1000 \times a_s^R}{L_{c_s^R}^2} \quad (3.10)$$

The average ERLE and ERTD of a set of route S from a route r can now be defined in Eq. 3.11 and 3.12.

$$\langle ERLE_{S,r} \rangle = \frac{1}{|S|} \sum_{s \in S} ERLE_{s,r} \quad (3.11)$$

$$\langle ERTD_{S,r} \rangle = \frac{1}{|S|} \sum_{s \in S} ERTD_{s,r} \quad (3.12)$$

3.3 Georgia Tech Flight Planner (GTFP)

A flight plan system in charge of determining what would be for the en route part the quickest wind optimal route from the airline point of view based on a set of available routes was computed.

Departure and arrival areas are subject to many unforeseen external parameters such as high congestion at the airports. The performance metrics defined in this thesis only focus on the en-route part of the flights. Although, the last F submitted and the actual trajectory A are provided, the airline's desired flight plan and its flight planner are not. Wind-optimal

flight plans based on an airline set of available routes were constructed using an ad hoc flight planner dubbed "Georgia Tech Flight Planner". The principle guiding the design of the GTFP is to rely on an automated process to produce a 4-dimensions representation of available trajectories and a ranking of the wind optimal routes. Each trajectory depends on many parameters (airspace information, weather conditions, aircraft information, user preferences and performances) regrouped that need to be defined and considered in the design of the GTFP.

3.3.1 Weather conditions

Weather conditions are the most influential causal factors when evaluating trajectory performance [**cheungsensitivity**]. Figure 4.1 shows that weather was the most important factor in en route delays in 2015. The most relevant causes of weather conditions are first the effect of storm activity that forces a re-routing of the aircraft and seconds winds by their significant impact on the time of flight. GTFP takes into account the wind conditions by extracting wind data from the NCDC server.

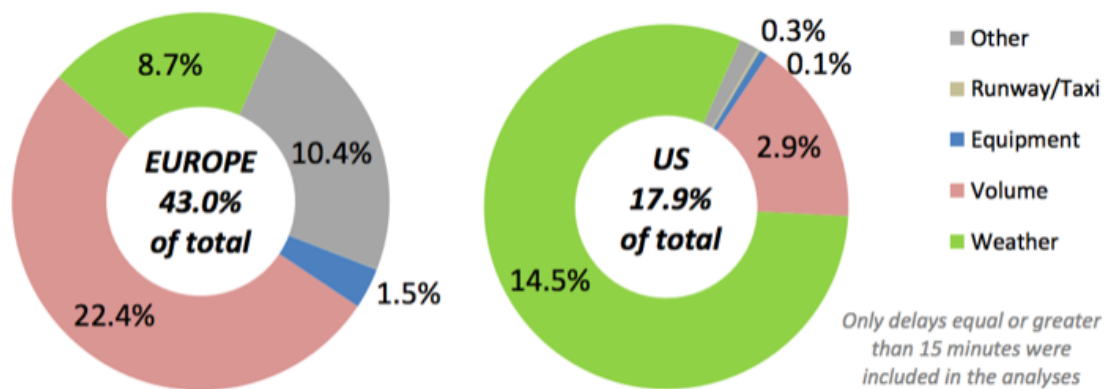


Figure 3.4: Breakdown of en-route ATFM delay by cause in Europe on the left and in the US on the right in 2015 (Source: [**PCR2016**]).

3.3.2 Airspace information

Airspace information such as restricted airspace due to military zones is necessary when computing flight plans. There is no universal and fixed airline set of preferred routes since airlines compute their flight plans from scratch every time while satisfying an infinite number of constraints. To take this restrictions into consideration, GTFP considers a very simple approach, compare to the complex flight plan systems of the airlines, by computing a flight plan among a set of possible routes. Let call $GTFP_R$ the set of possible routes r of the key city pairs studied. The larger the set of possible routes $GTFP_R$ is, the more precise the GTFP wind optimal route will be and the closer it will be from what would actually be the result of an airline flight planner. To increase the results accuracy and to be as realistic as possible, $GTFP_R$ is comprised of A_R set, PR set, CDR set and F set. The different datasets of the twelve city pairs listed in Table 3.1. Some city pairs such as SEA-SFO and SFO-SEA do not present any available routes; since the city pair is really close in distance, departure and arrival procedures overlap each other and do not enable any free en route procedures. Four city pairs do not present nether A_R nor F because the data is not available. From now on, the analysis will exclude these CP .

3.3.3 Aircraft information, user preferences and performance

Aircraft information, user preferences and performance including the cruise altitude and the aircraft's speed are also necessary. ETMS data is used to compute typical flight profile (altitude and speed) for each available route r of $GTFP_R$ of all the city pairs. To build the profile of r , we determine the nearest r for each recorded flight using the area as a measure of proximity. Each recorded flight and r are then divided in 100 points. Each profile is attributed the average air speed and altitude of all recorded ETMS data corresponding to routes deemed closest to this specific r . Since the recorded speed in ETMS is the ground speed, it is corrected with available weather data to provide the airspeed information for

Table 3.1: Number of ATC preferred routes and CDRs, number of airline main routes and number of filed flight plans for the twelve key city pairs studied in this thesis.

Origin	Destination	PR	CDR	A_R	F
LGA	ATL	3	23	0	0
ATL	LGA	1	11	14	520
LGA	MIA	0	25	31	179
MIA	LGA	2	0	11	179
JFK	MIA	5	27	37	94
JFK	MCO	3	21	40	128
JFK	SFO	1	67	66	207
SFO	JFK	1	30	54	207
SEA	ATL	0	0	12	255
ATL	SEA	0	9	0	0
SEA	SFO	0	0	0	0
SFO	SEA	0	0	0	0

each flight profile. For instance, the altitude and speed flight profiles of one r of the ATL-LGA city pair illustrated on Figure 3.5 is based on 26 recorded flights.

For a given F or A , GTFP determines what would be the corresponding ideal route I , the length of the en route part and the area between the A , F and I en route parts. However, every airline F is a list of way points without any time information. In order to enable possible time comparisons with I between the en route parts, FW is created with the GTFP speed and altitude properties. AW is also computed from A so that the comparisons between AW , FW and I are now only representative of the difference between the trajectories and congestion as long as they share the same user preferences and weather conditions. Fixing some parameters among airspace information, weather conditions, aircraft information, user preferences and performances enables the analysis of the influence of the others.

There are three steps in the GTFP:

- **Profiles construction:** for each available route r of the city pair CP studied, GTFP builds a flight profile (average speed and altitude) by using ETMS records.

- Flight plan study:** GTFP analyzes each filed flight plan of the key city pairs studied. For one specific F of a city pair CP , first GTFP associates F to its actual trajectory A and second combines the flight profiles built in the first step, aircraft information and weather conditions to compute temporal and spatial flight plan information of each possible route of the $GTFP_R$ set. GTFP defines I as the quickest wind optimal route among this $GTFP_R$ set. For this F studied and its corresponding A , GTFP also computes FW and AW defined in the nomenclature. They estimate the duration of each trajectory, using GTFP flight profiles and enable better comparisons with GTFP fastest wind optimal route I focusing on trajectory disparities only.
- Statistics Computation:** GTFP compares A , I and F by computing the en route lateral deviation (DA, I), the en route length efficiency ($ERLE_{A,I}$), and the en route time difference ($ERTD_{A,I}$) between AW , FW and I ($ERTD_{A,I}$), defined in Section 3.2. Statistics can be computed for each individual route, clusters of routes and for the whole city pair.

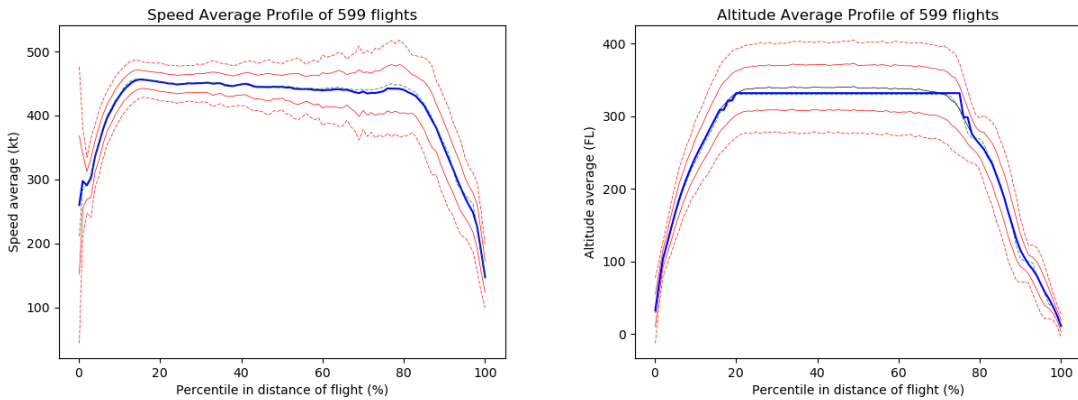


Figure 3.5: Speed average profile (on the left) and altitude average profile (on the right) of the available route RP of the city pair ATL-LGA computed with 599 ETMS flights data. The blue curve represents the average speed or altitude. The green is the median speed or altitude, and the red curves one and two standard deviations from the average speed or altitude.

CHAPTER 4

INTRODUCTION OF METRIC 1: EVALUATION OF ATC SET OF PREFERRED ROUTES

The objective of this chapter is to propose a candidate performance metric based on the analysis and evaluation of ATC set of preferred routes suggested to the airlines before take-off. This metric examines a more strategic aspect by studying how the flight plans are chosen.

4.1 Filed versus preferred flight plans: motivations

The goal of ATC is to minimize overall direct and strategic costs while maximizing the utilization of available capacity. ANPS have to make airlines objective their own, while having to optimize a number of complex trade-offs and achieve their first priority, safety. Figure 4.1 summarizes the most important factors of flight inefficiency depending on the phase of flight considered. As demonstrated in [Reynolds2008], the most important contributors of en route flight inefficiency (27%) are standard routes and restricted airspace. That inefficiency could be reduced by allowing more widespread use of flight away from the rigid airspace structure, as introduced by the "free routes" in Europe or the user-preferred routes [EurocAnnualReport], [PRR2015Eurocontrol] and [fuller2004enhanced].

Many airlines prepare their flight plans based on fixed routes catalogs (such as the set of preferred routes, Playbook routes and CDRs in the US and the RAD in Europe) generated by ATC and do not have the resources to benefit from shorter routes when available or the more cost-efficient route. One such case is Miami to New York where only one route is available over the water to avoid the congested land area along the east coast. Air operators had complained to ATC but not to avail. Analyzing these catalogs of preferred routes and the way airlines benefit from them can be an opportunity for increasing flight efficiency.

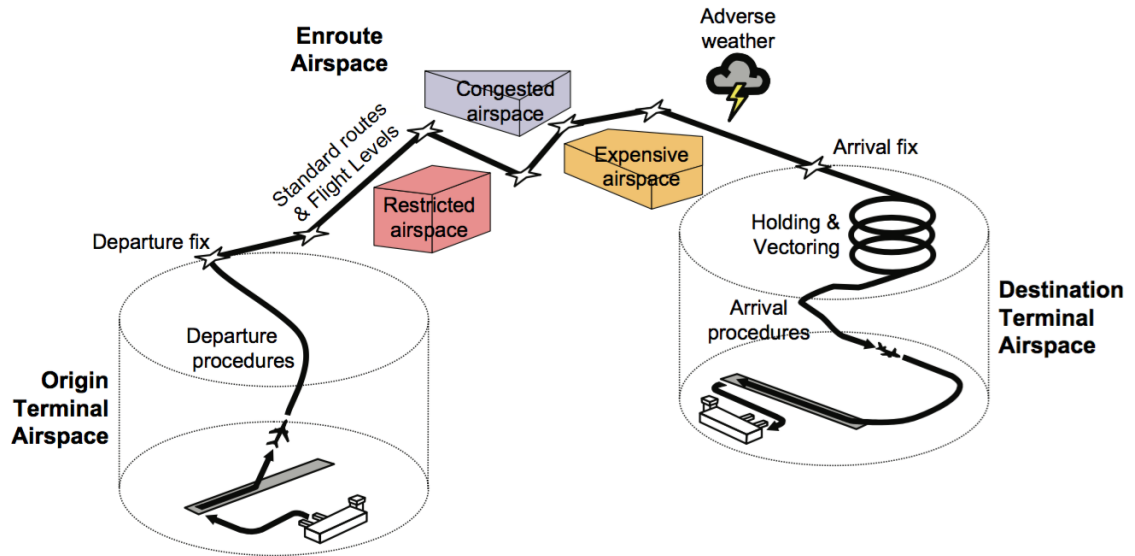


Figure 4.1: Potential causes of flight inefficiency depending on the phase of flight considered (Source: [Reynolds2008]).

The novelty of this new indicator is to consider the airline perspective as primary motivation in the process of flight planning.

Comparing ATC set of preferred routes available (PR set), ATC set of CDRs (CDR set) and the actual set of flight plans submitted by an airline before take-off (F set) provides useful insights regarding the relevance of the routes catalogs published by ATC. This new indicators aim at increasing efficiency while maintaining capacity and safety. The two stakeholders involved in this indicators are both ATC and the airlines.

4.2 Filed versus preferred flight plans: definition

To introduce new metrics, many criteria listed in Section 2.4 need to be defined. The KPI introduced in this Chapter performs in the KPA of efficiency. The analysis focuses only on the en route part of the flights in order to better target the en route efficiency mainly driven by ATC routing and to avoid the airport influence and TMA mostly related to congestion leading to airborne holding patterns. The metric also needs to be universal to be applicable to any systems or city pairs but also robust from one year to the next.

As introduced in Table 4.1, the KPI evaluates if the last flight plan filed by an airline is close to the set of preferred routes suggested by ATC. The indicator and its metrics' goals are to analyze the relevance of the set of PR and compute statistics for each PR . If F is systematically far from the set of PR , it may question the relevance of this set determined by ATC. It can be useful for both the airlines and ATC.

Table 4.1: KPI 1 introduced: Lateral deviation from the last filed flight plan and ATC set of preferred routes.

Indicator	Lateral deviation between the airline latest flight plan submitted before take-off and the ATC set of preferred routes for the en route parts.
Metric Name	Airline filed versus ATC preferred en route flight plans lateral deviation for Key City Pairs
Metric definition	Area between the flight plan and its closest preferred route among the ATC set divided by the square length of the closest preferred route and multiplied by the arbitrary length of 1000 NM. A system value is obtained by averaging over a period of time, for all the key city pairs. The metric measures are defined in eq. (3.9) and (3.10) where the set of preferred routes is PR set.
Unit	NM
Reporting scope	NAS Key City Pairs
Reported values	August 15th, 2014 to September 18th, 2014

4.3 Filed versus preferred flight plans: analysis and results

Analysis of the different sets

The metric introduced is evaluated for the US airspace with the data available presented in Section 3.1 obtained by the FAA and an American airline. The key city pairs studied in this thesis are extracted from the list of key city pairs defined by the FAA, reviewed and approved by NextGen Advisory Committee (NAC). The key city pairs, selected and used for our metrics computation, are a combination of long, short (KLGA-KATL, ATL-LGA), vertical (KLGA-KMIA, KMIA-KLGA, KJFK-KMIA, KJFK-KMCO and KSEA-KSFO, KSFO-KSEA) and horizontal (KJFK-KSFO, KSFO-KJFK, KSEA-KATL and KATL-KSEA) city pairs and are a good representation for the US NAS (K- for consistency). From now, A_R is said to be used by F when it is the closest to F .

In this section, both ATC sets of PR and CDR , defined in Section ?? are analyzed. Congestion in the US is mostly identified in the east part of the airspace. Therefore, the US airspace organization seems divided in two zones, approximately delimited by the Mississippi river. Due to very high congestion on the east coast, the airlines will not benefit from the flexibility they enjoy on the west coast when they file their flight plan. On the east coast, ATC usually imposes only one preferred route between two airports that the airlines have to file anyway. On the west coast, the airlines files their most economical flight plan determined by their own flight plan system. At the boarder of this virtual limit drawn from Minneapolis, MN, to Nashville, TN and Mobile, AL, ATC allows the airlines to file a flight plan among a list of 2 or 3 preferred routes. Moreover, for a cross-continental flight between SFO to ATL, the first part of the flight will mainly be cost efficient from the airline point of view and will then have to follow a route imposed by ATC once flying on the east part of the US airspace. The number of PR s and CDR s mainly depends on the location of the airports studied and both departure and arrival procedures as represented in Table 3.1. SEA-SFO, SFO-SEA, ATL-SEA or SEA-ATL do not have any PR imposed by ATC since the airports are located in a very weak congestion area and do not interfere with the NY metroplex. Usually, when flying toward NY metroplex, fewer PR are made available by ATC to control the high congested area.

4.3.1 Filed versus preferred routes: illustrated results

Comparison of 8 city pairs: The metric is computed for 8 city pairs across the US over a period of time of two months in Table 4.2. If F is always considered far from any PR , it may question the relevance of the selection of this set. The relevance of the PR set on the East coast is evaluated by analyzing the average deviation of the set of PR upon the set of F and the frequency of use of each PR . For ATL-LGA, MIA-LGA and JFK-MIA, the ATC set of PR can be considered respected from ATC perspective since the PR are in average not too far from the flight plans submitted by the airline (D_F^{PR} of 6.9, 6.3 and

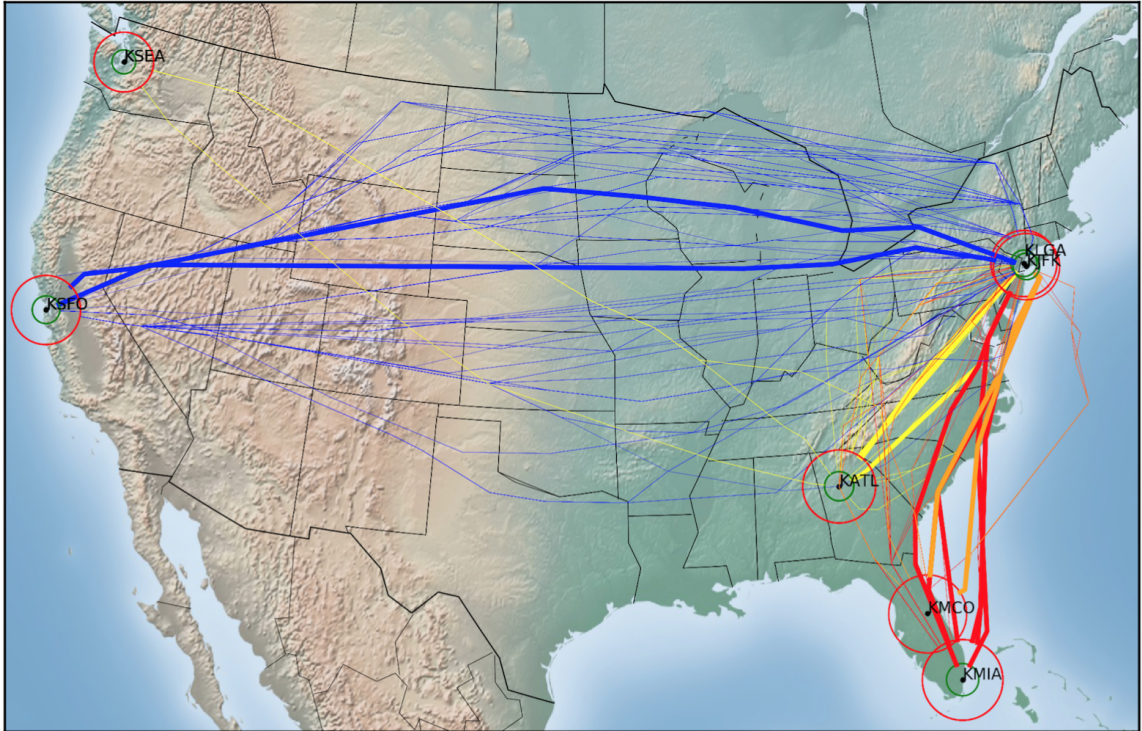


Figure 4.2: Datasets of all the FAA preferred routes (in boldface lines) and the FAA CDRs (in thin lines) for the key city pairs studied. The green circle represents the 40 first NM around the departure airport and red circle the last 100 NM around arrival airport.

6.3 NM, respectively). However, three out of five PR of JFK-MIA are not used by F set and could be removed from the set. For JFK-MCO, the average lateral deviation between ATC and F sets is 16.3 NM, and two out of 3 PR are used. Traffic is less dense on the West coast hence PR are not always mandatory for the airlines. That is why, only one PR is available for both JFK-SFO and SFO-JFK. The average lateral deviation of PR set upon the airline set of flight plans for both city pairs are really high (60.5 and 25.8 NM) because airlines do not have to follow PR all the time since the west coast is not very congested. Hence, the filed F can be far from PR . It is not very useful to analyze the relevance of all the PR of the whole city pairs since they are not always mandatory. More analysis are made in details for these city pairs with their clusters in the next paragraphs.

For each city pair studied, a graph representing the actual routes used by the set F (in green) is produced. The thickness of the PR routes (in blue), CDR routes (in yellow)

Table 4.2: Average normalized lateral deviation of the used preferred routes of PR and CDR for seven key city pairs in the US. The use of a PR in a set and its average normalized deviation from the filed F are useful information to analyze the relevance of a preferred routes dataset.

City Pair	D_F^{PR} (NM)	Used/Total	D_F^{CDR} (NM)	Used/Total
ATL-LGA	6.9	1/1	4.3	3/11
LGA-MIA	0.0	0/0	5.1	7/25
MIA-LGA	6.3	2/2	0.0	0/0
JFK-MIA	6.3	2/5	4.1	6/27
JFK-MCO	16.3	2/3	6.0	4/21
JFK-SFO	60.5	1/1	10.5	18/67
SFO-JFK	25.8	1/1	9.8	17/30
SEA-ATL	0.0	0/0	0.0	0/0

or A_R routes (in red) is representative of its frequency of use by F set. The results are computed for the period of time of the dataset available.

ATL-LGA: The city pair ATL-LGA has only one PR available, which is similar to one A_R since their lateral deviation is 0 NM. This single PR is used by all the filed flight plans with a lateral deviation of 5.85 NM. Consequently, the set of PR is relevant for this city pair. The metric results underlines the very high congestion area on the East coast of the US and next to the NY metroplex that constrains airlines to follow the unique route available imposed by ATC to ensure safety and capacity. Indeed, ATC imposes this route for all flights even in bad weather conditions. In general, for 520 F filed, \hat{D}_F^{PR} between the unique PR and F is 6.87 NM whereas it is of 4.04 NM between the most used A_R and F . Nevertheless that PR may not be nether relevant nor optimal from the airline point of view by comparing it with what could be a wind optimal route developed in the next chapter. Moreover, one may wonder why 7 F fly far from the PR .

LGA-MIA and MIA-LGA: For the city pair LGA-MIA, although there is no PR , 25 CDR spread out on both the continent and ocean sides are available. In facts, only 2 CDR s are mainly used by F with 44.1% and 42.5% as represented on the first graph of Figure 4.3, with \hat{D}_F^{CDR} of 2.84NM and 4.56NM, respectively. Those CDR s are very similar to

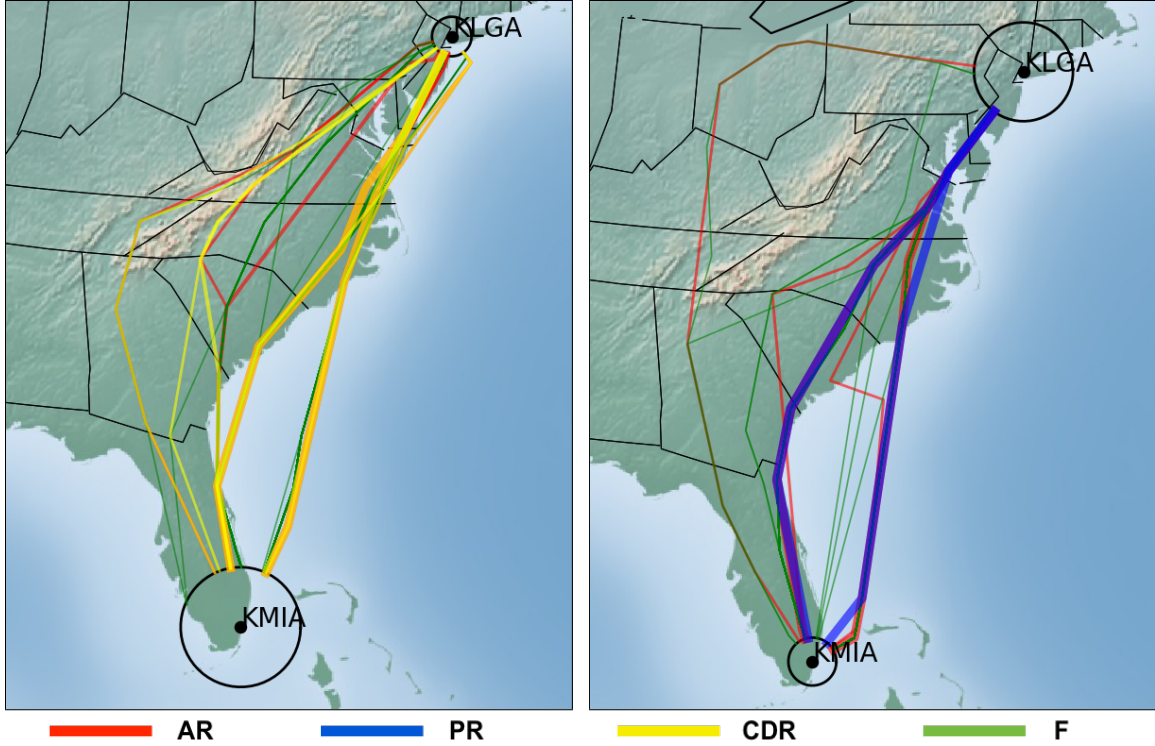


Figure 4.3: Illustrated results of metric 1 on the city pairs LGA-MIA and MIA-LGA with the set F (green), PR (blue), A_R (red) and CDR (yellow), with the line width function of the use of the route.

two A_R (0,6NM of normalized deviation for both), which are even closer from the F filed (2.54NM and 4.21NM). Around 13% of F set uses other routes on the continental side. The restriction of the space to the use of only two main routes flying on the ocean side and on the coastline are strongly linked to the high congestion of this area and the fact that some aircraft have the equipments required to fly over sea while other do not.

For the city pair MIA-LGA, A_R seem quite similar to the one of LGA-MIA and ATC suggests two PR but 0 CDR . In facts, both PR are used equally (53.1% and 46.9%) by F set with \hat{D}_F^{PR} of 6.92NM and 5.57NM from F set. Similarly, two A_R are used by F equally (50.3% and 46.9%) with $\hat{D}_F^{AR} = 2.95$ NM and 0.69 NM, respectively. Consequently, PR seems to be relevant but F set is closer from A_R than PR . It may be interesting for ATC to adapt their PR set closer to the airline's preferences.

The existence of PR set for MIA-LGA and absence for LGA-MIA could be linked

to the very high congestion next to NY metroplex that forces ATC to impose mandatory routes to ensure safety and capacity next when arriving next to NY area whereas airlines are more free to leave it and fly toward a less dense area.

JFK-MIA and JFK-MCO: While A_R and CDR set seem similar for both city pairs on Figure 4.4, there are 3 PR available for JFK-MCO and 5 PR for JFK-MIA. The two city pairs are most likely to be sharing the same routes. However, whereas only one PR along the coast line is used by 96.1% of F set for JFK-MCO (with $\hat{D}_F^{PR}=16.8\text{NM}$), two of them (one following the coast line and one on the ocean) are used by 76.6% and 23.4% for JFK-MIA (with $\hat{D}_F^{PR}=4.57\text{NM}$ and 11.81NM, respectively). Finally, whereas most of the routes for JFK-MCO follow the coastline, the most used one is located on the ocean for JFK-MCO. That tendency can be linked to the motivation of increasing safety and reducing dense areas on the JFK-MCO road by spreading JFK-MIA routes further from the coastline as long as aircraft are well equipped to fly far from the coast. The metric shows that some PR are not used: 2 for JFK-MCO and 3 for JFK-MIA could be removed from the sets. Moreover, the PR could be adapted to the A_R mostly used by F to favor the airlines preferences. It could be interesting to understand why a few F do not follow PR and follow routes on the continent where congestion could be higher. Moreover, the choice of coastline routes versus ocean routes may be explained for cost efficiency reasons with the winds developed in the next Chapter.

JFK-SFO SFO-JFK: Compared to the previous CP studied, these long distance horizontal CP have both one single PR , around 30 and 60 CDR illustrated on Figure 4.5. CDR and A_R seem to be similar for both CP and largely spread out between the two airports. However, all the routes merge into a restricted number of points when departing or landing at both airports because of departure and arrival procedures. For both CP , the deviations between CDR and F are pretty high for the different clusters with \hat{D}_F^{CDR} of 11.8, 13.6 or 17.8NM for JFK-SFO and 12.9, 5.5 and 12.0 NM for SFO-JFK. Finally, the

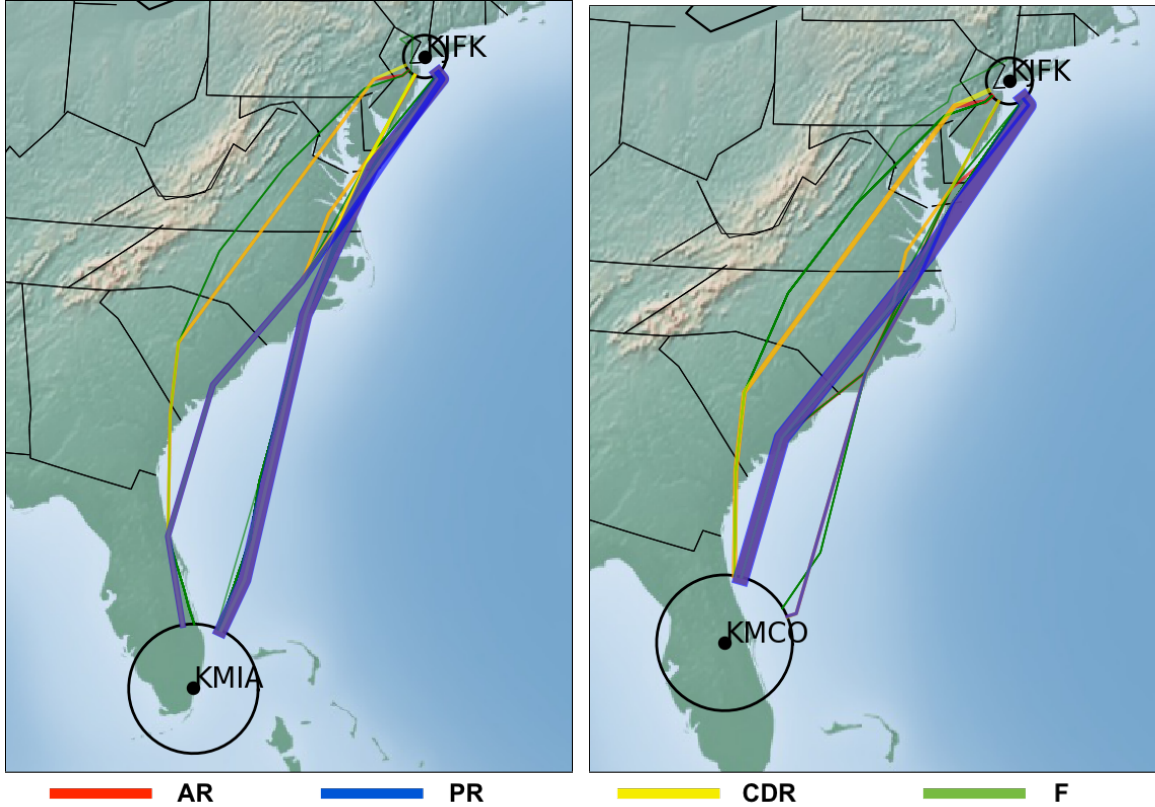


Figure 4.4: Illustrated results of metric 1 on the city pairs JFK-MIA and JFK-MCO with the set F (green), PR (blue), A_R (red) and CDR (yellow), with the line width function of the use of the route.

CDR set does not seem to be relevant and the routes could be redesigned to match the airlines preferences better. For each CP , PR is barely used by F set with a deviation $\hat{D}_{FPR}=60.5\text{NM}$ in average for JFK-SFO compared to 25.8NM for SFO-JFK. It will be interesting to compare the F set with what could be a wind optimal route to understand the disparity of F set.

4.4 Metric 1: interpretation

The first indicator analyzes the relevance of ATC set of PR . The metric defines the lateral deviation between a flight plan and a preferred route, and is computed for each filed F . An average value for the entire set is also computed to evaluate the relevance of the set. The lateral deviation has been normalized and enables comparisons between any CP of

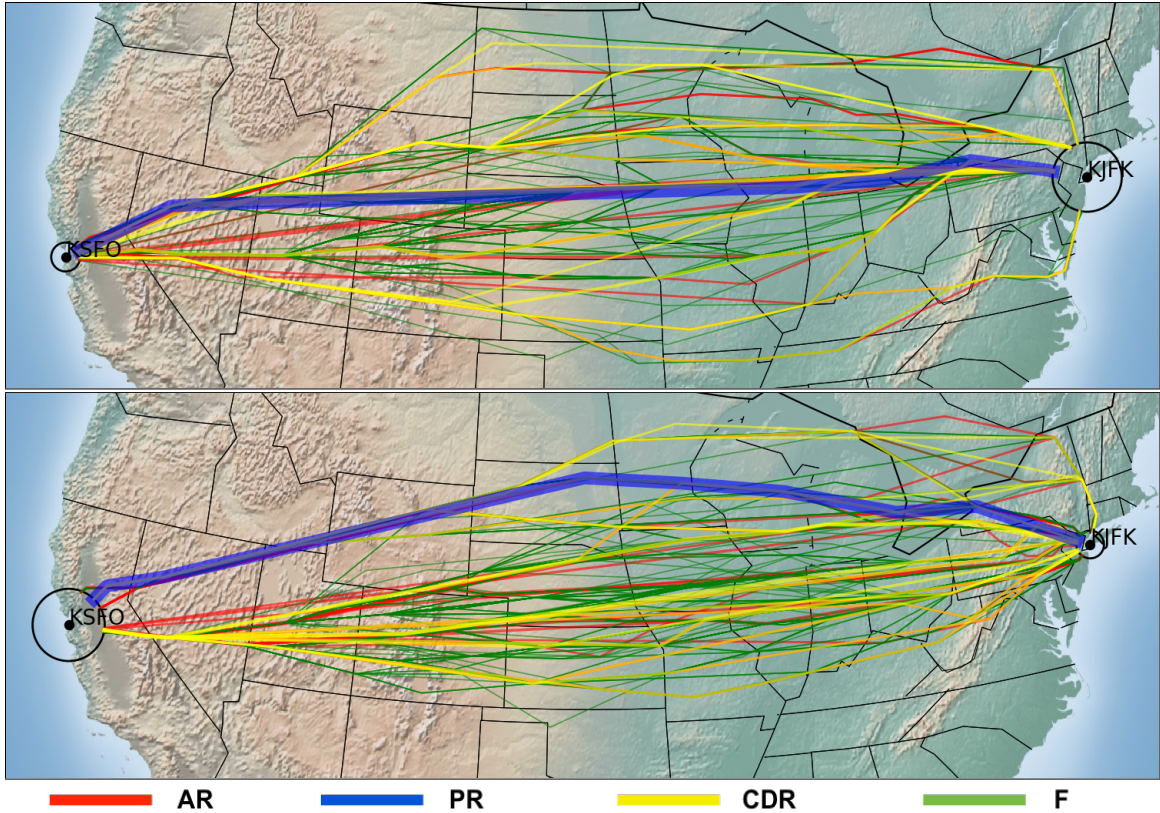


Figure 4.5: Illustrated results of metric 1 on the city pairs SFO-JFK and JFK-SFO with the set F (green), PR (blue), A_R (red) and CDR (yellow), with the line width function of the use of the route.

different lengths. The metrics defined are universal as they enable comparisons between different preferred routes but also different city pairs. Upon the different key city pairs studied, the eastern city pairs show relevant preferred routes and are mainly used. PR sets of long range city pairs could be improved or changed in order to fit more with the actual filed flight plans. These metrics are wanted to be robust to make comparisons from one year to another. They are useful for ATC to evaluate the choice of their preferred routes set in order to better match the airlines preferences, which should be one of their main priority.

CHAPTER 5

DEFINITION OF NEW METRICS BY INTRODUCING A NEW IDEAL FOR EN ROUTE EFFICIENCY INDICATORS

The objective of this section is to propose candidate performance metrics based on the analysis and evaluation of the en route parts of the actual trajectory and the last filed flight plan by introducing a new ideal trajectory. The novelty of this metric lies in the choice of the ideal trajectory that is not longer based on the achieved or direct distance between the two airports but on what is considered be the most preferred route from the airline perspective. Studies of actual trajectories have already been conducted. But rather than exploiting the trajectories post-flight, this paper examines a more strategic aspect by studying not only how the decisions are taken before take-off, but also how the flight plans are chosen.

5.1 Motivations

So far, in order to analyze the en route flight efficiency, analyzed (filed and actual) trajectories were compared to an ideal flight based on the achieved distance or the direct distance, as developed in Section 2.3.3. Both the FAA and EUROCONTROL agree that there are several caveats in using such a benchmark in the metric computation.

- The ideal trajectories do not include the vertical component
- The benchmarks do not consider external parameters such as SUA, congestion and weather conditions. The aircraft is considered to be the only actor in this unachieved ideal situation
- The benchmarks are usually the shortest in distance but are not the most economical flight from the airlines' perspective since it does not consider the effect of the winds which have a huge impact on the determination of the airline preferred flight plan

There is a need to develop a new benchmark that would better consider the previous parameters into consideration in the ideal trajectory computation. The particularity of this benchmark is that it will be based on the airline point of view. Many parameters, described in Figure ??, influence the choice of a flight plan before take-off. Most precisely, en route efficiency is influenced by weather conditions (winds effect and severe weather conditions), restricted (SUA), expensive and congestion airspace. Winds have the most important effect in the determination of the most cost-efficient flight. The goal of this indicator is to compute an ideal route for each analyzed trajectory with GTFP based on a set of possible routes that already considers the SUA, combined with weather and winds conditions in the means of determining what would be the wind optimal route based on that specific set of available routes.

5.1.1 Metrics definitions

The indicators developed are a comparison of both filed flight plans submitted to ATC before take-off and actual trajectories with a new ideal: the quickest wind optimal route based on a set of possible routes. For each filed flight plan or actual trajectory, GTFP determines what would be the ideal flight in the same conditions. Different measures are developed for these indicators: the lateral deviation of the en route parts of the analyzed (filed and flown) trajectories from the ideal and the en route comparison in length and time between the routes.

The three KPIs perform in the KPA of Efficiency (while maintaining capacity and safety). They are specific to the en route parts of the flights and aim at increase the en route flight efficiency, most specifically from the air carriers perspective. They can be useful for both the airlines and ATC.

Lateral deviation between the two en route parts: This metric developed in Table uses the lateral deviation computation defined in section 3.2. For each filed flight plan F or

actual trajectory A , GTFP computes the lateral deviation between the analyzed trajectory and the ideal I by dividing the lateral area between the two routes with the length of I as defined in Eq. (3.10). Some actual trajectories include holding patterns not only in the terminal area with the high congestion due to the airports infrastructures but also during the en route parts. In order to avoid redundancy and complexity in the area computation, the area related to the holding patterns is not taken into consideration. The holding patterns due to high congestion is already analyzed in the metrics analyzing the length and time differences.

Table 5.1: KPI 2 introduced: En route Lateral deviation of the filed flight plan (actual trajectory) from the ideal route based on a set of available routes.

Indicator	En route lateral deviation of the airline latest flight plan (or actual trajectory) from the ideal route.
Metric Name	Filed (or flown) Flight versus ideal en route lateral deviation for Key City Pairs
Metric definition	En route area between the airline flight plan (or actual trajectory) and the ideal route among a set of available route divided by the square length of the ideal and multiplied by the arbitrary length of 1000 NM $D_{F,I}$, Eq.(3.9). A system value is obtained by averaging over a period of time, for all the key city pairs $\langle D_{F,I} \rangle$, Eq. (3.10).
Unit	NM
Reporting scope	NAS Key City Pairs
Reported values	August 15th, 2014 to September 18th, 2014

Comparison in length between the two en route parts: developed in Table 5.2. For each filed flight plan F or actual trajectory A , the En Route Length Efficiency (ERLE) from the ideal is computed. The ERLE defined in 3.2 measures the additional distance (in %) of the analyzed trajectory with respect to the ideal.

Comparison in time between the two en route parts: developed in Table 5.3. For each filed flight plan F or actual trajectory A , the En Route Time Difference (ERTD) is computed. The ERTD defined in 3.2 measures the additional time (in minutes) of the

Table 5.2: KPI 3 introduced: En route length efficiency between the filed flight plan (or flown trajectory) and the ideal route based on a set of available routes.

Indicator	En route length efficiency between the airline latest flight plan (or actual trajectory) and the ideal route.
Metric Name	Filed (or flown) Flight versus Ideal En Route Length efficiency for Key City Pairs
Metric definition	En route distance difference between the airline latest filed flight plan (or flown trajectory) and the ideal route among a set of available routes divided by the length of the ideal $ERLE_{F,I}$, Eq.(??). A system value is obtained by averaging over a period of time, for all the key city pairs $\langle ERLE_{F,I} \rangle$, Eq.(3.11).
Unit	%
Reporting scope	NAS Key City Pairs
Reported values	August 15th, 2014 to September 18th, 2014

analyzed trajectory with respect to the ideal. The challenge of this time analysis is that both last flight plans submitted by an airline and the ideal trajectory require speed and altitude information that are only known by the pilots who refer to the airline. The ideal trajectory related to a specific flight plan (or actual trajectory) needs to be computed in the exact same conditions as the analyzed route ones to be able to make relevant and significant comparisons.

Table 5.3: KPI 5.1 introduced: En route time difference between the filed flight plan (or flown trajectory) and the ideal route based on a set of available routes.

Indicator	En route time difference between the airline latest filed flight plan (or flown trajectory) and the ideal route.
Metric Name	Filed (or flown) Flight versus ideal trajectories en route flight time for Key City Pairs
Metric definition	En route time difference between the airline latest filed flight plan (or flown trajectory) and the ideal route among a set of available routes $ERTD_{F,I}$, Eq. (??). A system value is obtained by averaging over a period of time, for all the key city pairs $\langle ERTD_{F,I} \rangle$, Eq. (3.12)).
Unit	minutes
Reporting scope	NAS Key City Pairs
Reported values	August 15th, 2014 to September 18th, 2014

5.2 Illustrated results

5.2.1 Analysis of different city pairs

The difference in duration, length and lateral deviation between the en route parts of F , A and I are computed for the overall key city pairs across the US and their clusters in Table ?? of the Annexe .

5.2.2 East cost short city pairs

The city pairs ATL-LGA, LGA-MIA, MIA-LGA, JFK-MIA, and JFK-MCO are located in the same high congestion area. The section 4 has shown that there is usually one or two used preferred routes imposed by ATC. The question now is to know if those preferred routes correspond to wind optimized routes.

For all these city pairs, the average deviation between the actual trajectories and their corresponding flight plans shows that A and F are geographically close ($10\text{NM} \leq \langle D_F^A \rangle \leq 24\text{NM}$) and almost equal in time and distance (average absolute time difference between 0 and 1 min and $-0,41\% \leq \langle ERLE_{A,F} \rangle \leq 1,06\%$). Therefore, the results of the second metrics for A and F will be very similar and there is no need to mention both.

For ATL-LGA, the en route time difference between A , F and I are close to zero. For this city pair, F and A are well optimized with the winds and really similar to the ideal. The average lateral deviation between A and I is pretty small (26NM), hence PR imposed by ATC is well optimized in time, distance and regarding the winds as illustrated on Figure 5.1.

For MIA-LGA, as shown on Figure 5.3, the Ideal route is located between the two preferred routes mainly used. The en route lateral deviations between both F and A from I are consequently higher for this city pair (73 and 70NM, respectively). In average, A and F are really close in time and length, there is no unexpected events rerouting the aircraft during the en route phase. The two clusters mainly used, which follow the two PR

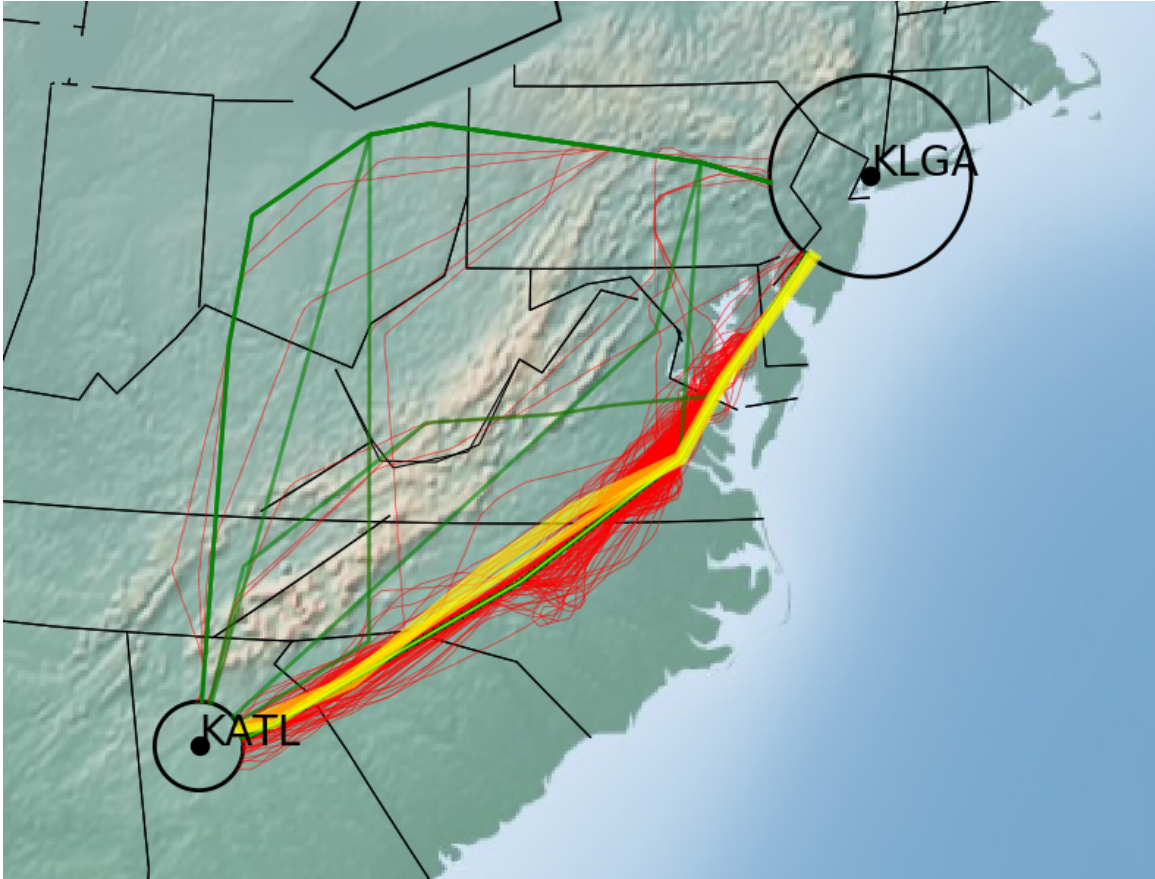


Figure 5.1: Illustrated results of indicators 2 on ATL-LGA for the en route parts of the filed flight plans (green), actual trajectories (red) and ideal route (yellow).

imposed by ATC, are not well wind optimized and longer than I ($\langle ERLE_A^I \rangle = 5.78\%$) but as efficient as I ($\langle ERTD_A^I \rangle = 6$ min).

For JFK-MIA and LGA-MIA, there are two clusters mainly followed. The first one, over the ocean, is almost always the Ideal trajectory. The second, is over the land and far from the Ideal. The $\langle ERTD_{A,I} \rangle$ is around 3 min for the ocean trajectories of LGA-MIA (respectively 6 min for JFK-MIA), while it is 7 min for the overland trajectories (respectively 8 min). This tendency is the same for the $\langle ERLE_{A,I} \rangle$ (around 3% and 2.5% versus 6% and 5% for both CP). A possible reason is that some airplanes are not able to fly over the ocean owing to the lack of equipments constraining them to take the overland route.

For JFK-MCO, the most used cluster (84,3%) that seems parallel to the Ideal ($\langle D_{A,I} \rangle$

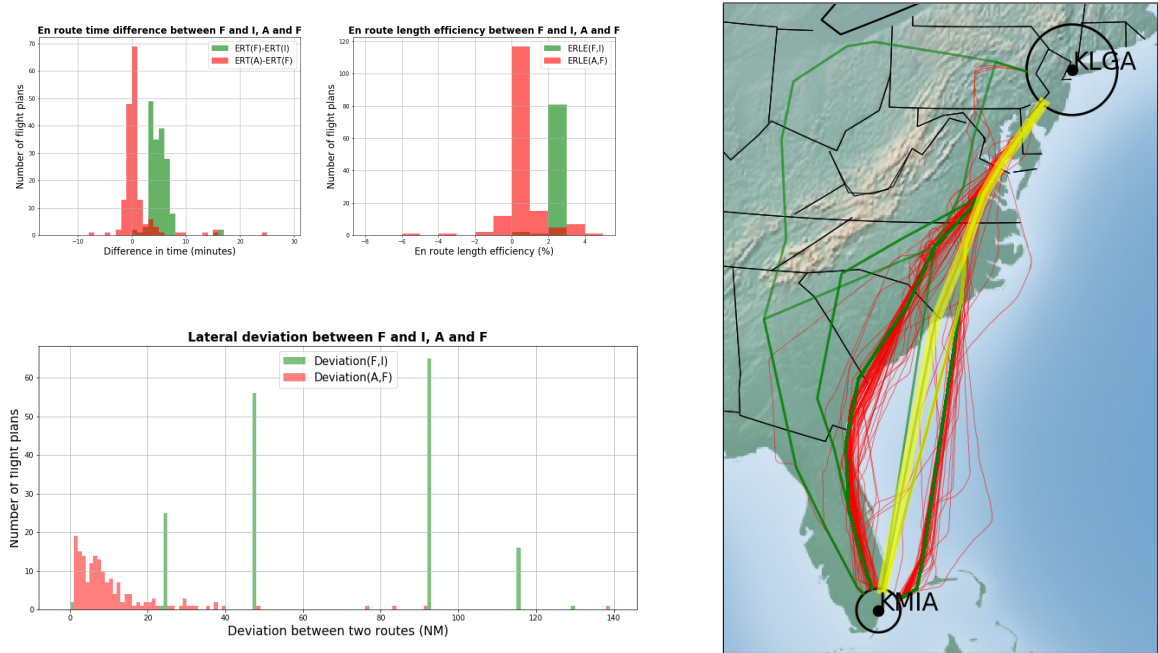


Figure 5.2: Illustrated results of indicator 2 on MIA-LGA: time difference, length efficiency and lateral deviation for the en route parts of the filed flight plans (green), actual trajectories (red) and ideal route (yellow).

around 56NM), shows good results for the $\langle ERTD_{A,I} \rangle$ of 4 min and an $\langle ERLE_{A,I} \rangle$ around 3%. The PR imposed by ATC seems well wind optimized.

Globally on the east cost, the actual trajectory and the flight plan follow ATC imposed PR , which are mainly wind optimized except for MIA-LGA.

5.2.3 Long range City pairs

For the long range city pairs like JFK-SFO, SFO-JFK, the first metric has shown the limitation of having a few numbers of PR .

Figure 5.4 shows multiple wind Ideals, which confirms the limitation of having a few number of PR . Therefore, the results of the lateral deviation between A and I are always high for both city pair and for all the clusters of the city pair ($\langle D_A^I \rangle > 92\text{NM}$ for the whole JFK-SFO city pair and 65NM for SFO-JFK). The en route time difference between A and I is around 6 min for SFO-JFK and 10min for JFK-SFO. The en route length efficiency is low for both with around 0% for JFK-SFO and around 1% for SFO-JFK.

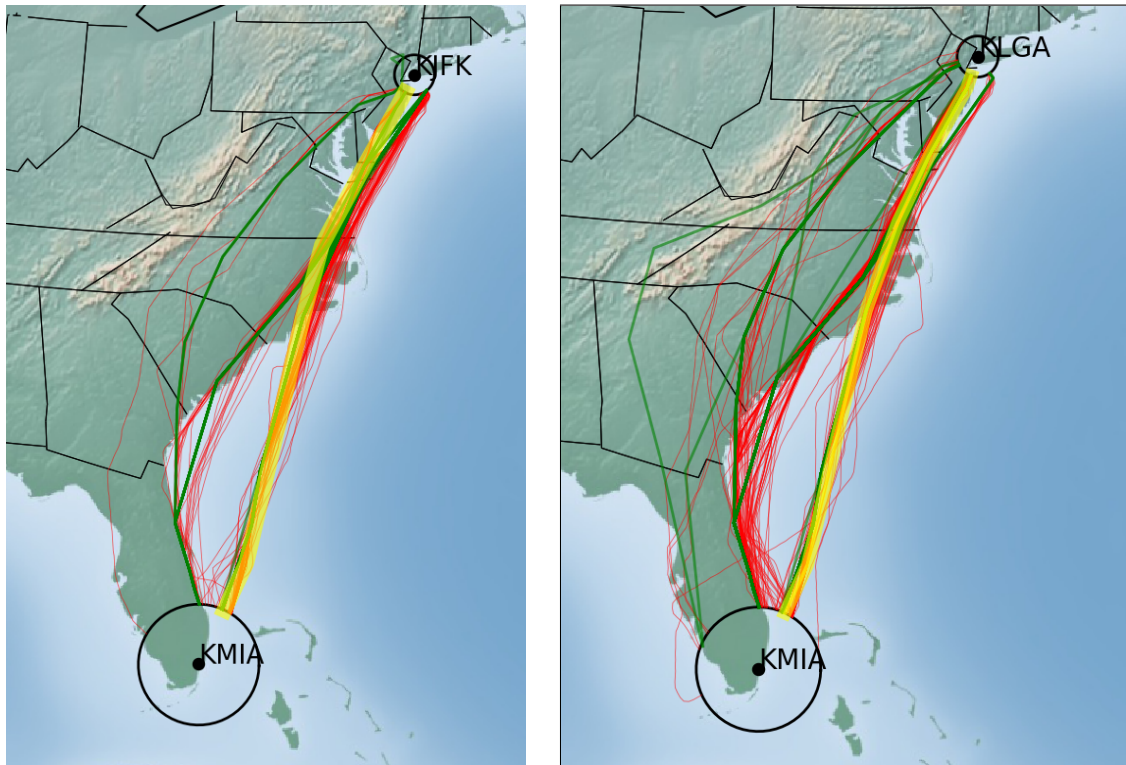


Figure 5.3: Illustrated results of indicators 2 on the short vertical city pairs: JFK-MIA and LGA-MIA for the en route parts of the filed flight plans (green), actual trajectories (red) and ideal route (yellow).

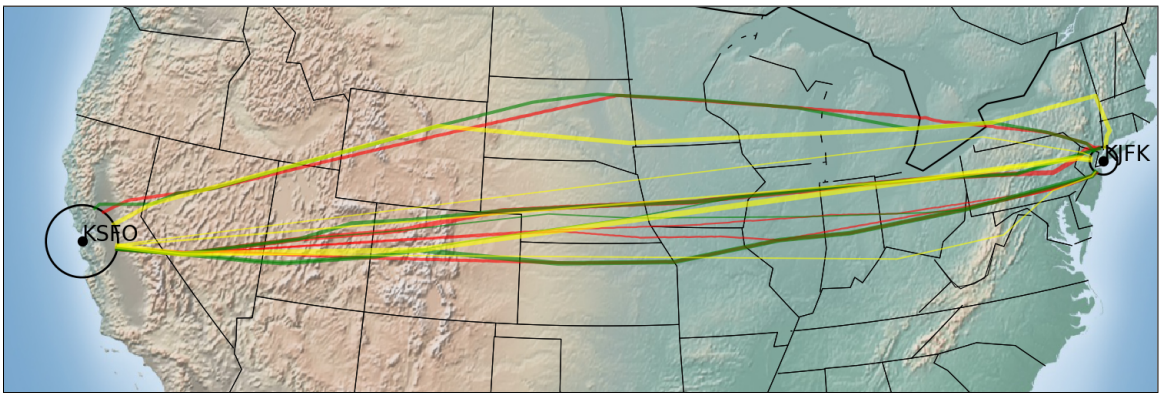
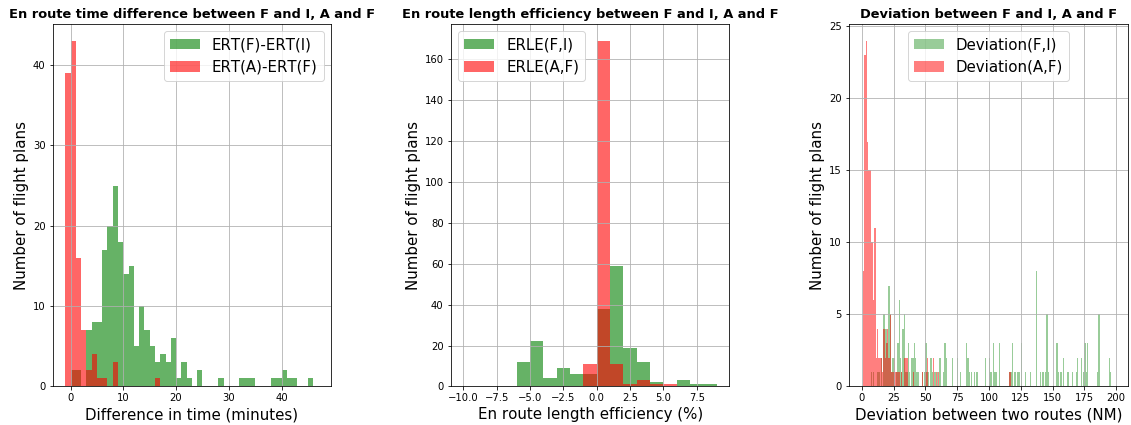


Figure 5.4: Illustrated results of indicator 2 on JFK-SFO: time difference, length efficiency and lateral deviation for the en route parts of the filed flight plans (green), actual trajectories (red) and ideal route (yellow).

Here it is clear that the interpretation of the metric relies on the flight planner used. Therefore, for the long range city pair, the limitation of GTFP, which is only based on a finite set of possible routes, is underlined. Nevertheless, the method and the metric introduced seem relevant. Possible improvements of the flight planner could be introduced. Computing not one, but several Ideals, which in reality is possible, would probably enhance the results of the lateral deviation. Furthermore, airlines flight planners compute a route in its integrability. The use of those kind of flight planners would definitely improve the interpretation of the metric but would need an important amount of resources in term of time, computation performances and algorithms. Indeed, actual airline flight planners have been developed for more than ten years.

5.3 Interpretation metrics 2

The comparison of filed or flown trajectories in time, length and deviation with respect to a new ideal based on the airlines perspective is the novelty of these metrics. These metrics have been analyzed for seven city pairs across the US for a two months period of time and evaluate the efficiency of both filed flight plans and actual trajectories with respect to the wind optimal route. The introduction of this new ideal also enables deeper analysis concerning the evaluation of ATC set of PR , developed in Section 4, by determining if these PR are well wind-optimized. The metrics are universal since they can be applied for any airspace and any city pair. However, the computation of the wind optimal route requires a set of available routes of each city pair studied. Comparisons can be made between different analyzed trajectories but also between different city pairs. The metrics are also robust since they can be computed for different periods of time and enable possible comparisons from one year to another. the metrics can be used individually but also combined together. For instance, a short deviation and big length difference are characteristic of holding patterns, a small length difference and large deviation refer to a route far from the ideal but having the same length.

This new ideal is based on the air-carriers point of view. However, even the wind-optimal route might not necessarily correspond to the choice of the airspace users because they might use different measures based on total costs (time, route charges, etc.) Many parameters considered in the airlines flight plans systems to determine their most cost economical flight are not available. GTFP developed is a proxy flight planner that determines the wind optimal route among a set of available routes for each city pair. Future work can focus on the improvement of GTFP in order to have it more similar to the airlines flight planner. The next step will be the determination of flight plans from scratch every time with a dynamic computation among a set of way points and jet routes. It could be interesting to have a ranking of different routes. Indeed, it is possible to have two Ideals, which are not

located in the same area. Future work will also include the vertical component in the en route flight efficiency indicators.

CHAPTER 6

CONCLUSION

6.1 Summary of Thesis Achievements

Four metrics are proposed in this paper. The first metric is the evaluation of the relevance of ATC set of preferred routes by analyzing its proximity with filed flight plans. Metric 1 is useful for the airline and the FAA regarding the determination of the set of preferred routes imposed by ATC in high congested areas. The three other metrics rely on the introduction of a new ideal of en route flight efficiency based on the airlines perspective that considers external parameters such as SUA and the winds conditions, which are the main reason of en route flight inefficiency. The three metrics are the comparisons of the en route parts between filed or flown trajectories with the wind optimal route based on air-carriers point of view.

The second metric, which is the comparison of the lateral deviation, is useful to analyze how wind-optimal the flight plans submitted before take-off and the actual trajectories are. The illustrated results of metric 2 on both long or short distance city pairs shows that the majority of flight plans have been well optimized considering the winds.

The third metric, which compares the flight plans and the real flights with the wind optimal route in duration gives an idea of the potential changes between the flight plans and the flights. It also shows the impact of unpredictable events such as congestion. The analysis on different city pairs show that it can be apply for long-range flights as well as short-range flights.

The fourth metric, which compares the flight plans and the real flights with the wind optimal route as additional distance flown gives insights about the length efficiency of the flight plan filed before take-off or the actual trajectories. It also shows the impact of

unpredictable events such as congestion when compared to metric 2: when a high additional distance is noticed with the same lateral deviation.

6.2 Future Work

Future studies will focus on isolating different parameters such as congestion and weather conditions. The differences in duration, length and lateral deviations can be computed for the same city pairs studied in this paper for a different period of the year to analyze the weather influence or for different hours during the day to analyze the influence of the congestion. The integration of the vertical component to evaluate the en route flight efficiency is another future work to be considered.

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