MASTER THESIS

Introducing required times of arrival to pre-defined routes to enhance sequencing and merging in terminal airspace: A case study for Frankfurt airport PSA25N arrival route

Justinas Alekna

SUPERVISED BY

Dr. Xavier Prats
Ramon Dalmau

Universitat Politècnica de Catalunya
Master in Aerospace Science & Technology

October 2017

This Page Intentionally Left Blank

Introducing required times of arrival to pre-defined routes to enhance sequencing and merging in terminal airspace: A case study for Frankfurt airport PSA25N arrival route

BY

Justinas Alekna

DIPLOMA THESIS FOR DEGREE

Master in Aerospace Science and Technology

AT

Universitat Politècnica de Catalunya

SUPERVISED BY:

Dr. Xavier Prats

Ramon Dalmau

Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels (EETAC)

This Page Intentionally Left Blank

ABSTRACT

This Master thesis proposes to handle peaks of air traffic in terminal airspace without using open-loop vectors from air traffic control (ATC) by combining the assignment of the Required Time of Arrivals (RTAs) at a metering fix with a set of pre-defined routes, taking advantage of the flexibility that procedures such as the tromboning provide in the lateral domain. RTA time window might be achieved by using common metering waypoint for all possible routes that can be provided by the tromboning procedure. Negotiating between ATC and on board equipment should lead to both side acceptable RTA that would fall in the frames of the RTA time window and would not jeopardize a constant flow of arriving traffic. The biggest advantage of such concept is that full route and distance to the runway is known in advance and onboard Flight Management System (FMS) is capable to perform Continuous Descend Operations (CDO) that satisfies fuel efficiency and environmental requirements not impairing the capacity of the airport.

Frankfurt Main airport's PSA25N Standard Arrival Route (STAR) was used to study the concept. For each possible shortcut of this tromboning procedure the feasible time windows (difference between the latest and earliest time of arrival) have been computed using numerical optimization. These approach time windows (ATW) are based on the computation of the earliest and latest arrivals to the metering. An in-house trajectory optimization software (Dynamo) was used to simulate these ATW for several possible shortcuts. A Batch script was developed to automate the simulations, as over 200 simulations had to be performed with different inputs for Dynamo. This batch script is added to the thesis as an appendix. Simulations were performed for energy-neutral (idle descent without speed brake usage), powered (thrust and/or speedbrake allowed) and fuel optimal approaches. A distance sensitivity analysis is presented.

Results revealed that over 14 minutes of ATW might be obtained with engine-idle CDOs. This time window might be widen up to 21 minute by allowing to the use of thrust and speed-brakes at the expense of burning more fuel and producing more noise (powered descents). Results also demonstrated that for a given RTA, very distinct shortcuts could be assigned such that the RTA fits into the associated feasible RTA window.

This Page Intentionally Left Blank

Table of Contents

This Page Intentionally Left Blank

List of figures

List of tables

This Page Intentionally Left Blank

INTRODUCTION

Geneva, 14 October 2014 – the International Air Transport Association (IATA) released its first 20-year passenger growth forecast, projecting that passenger numbers are expected to reach 7.3 billion by 2034. That represents a 4.1% average annual growth in demand for air connectivity that will result in more than a doubling of the 3.3 billion passengers that traveled in 2014[1].

A wide number of issues have to be solved to support such a growth of air traffic, such as the limited capacities of the airfields and their infrastructure, lack of qualified staff, limited abilities of current Air Traffic Management (ATM) system, etc. All these limitations undoubtedly lead in to significant delays and/or non-efficient operations, preventing further development of air transport. Factors like airport facilities are relatively easily solvable with sufficient investments, while ATM issues require deep studies, innovative ideas and novel systems to be implemented.

Moreover, the reduction of the environmental impact of aviation without compromising capacity is one of the major drivers of current research efforts in air transportation. Continuous descend operations (CDO) aim at executing optimal engine-idle descents to reduce both fuel consumption, gaseous emissions and noise nuisance in the terminal maneuvering area (TMA). In order to compute the optimal descent profile, the remaining distance to go to the runway threshold must be known by the on-board FMS.

However, in busy TMAs this condition rarely occurs, since aircraft are tactically vectored by the air traffic controllers (ATC), which stretch the descend path to maintain safe separation between aircraft and optimize sequencing and merging operations. In addition, neither the duration of the vector instruction nor how the aircraft will re-join its initial routing it is not known by the aircraft crew. As a result, it is not possible to predict the remaining distance to go and state-of-the-art FMS are not able to optimize the trajectory to achieve the most environmentally-friendly descent profile [2].

One objective of the future ATM paradigm is to remove these open-loop vectoring instructions from their day to day operations and start to use Required Times of Arrival (RTA) procedures to sequence and merge arrival traffic at one or more metering fixes along the arrival route. Nevertheless, replacing radar vectoring only with RTA assignments might not be enough to accommodate all arrival traffic for some peak traffic scenarios, as it was reported, for instance in [3].

This Ms. Thesis proposes to complement RTA assignment with different lateral route options in a tromboning approach procedure. The objective is to enlarge the RTA feasible time window aiming at enabling CDO as much as possible, even in dense TMAs. Thus, it is proposed a solution to enable CDOs from the cruise level to the runway threshold. The main idea is to separate, sequence and merge arriving traffic by negotiating not only RTAs but also the shortcuts, taking advantage of the flexibility provided by tromboning procedure in the lateral domain. The motivation is to achieve a strategy where no open-loop vectors are given during the execution of the descent, facilitating the planning and execution of the optimal CDOs. The route clearance (including the waypoints in the sequencing leg where the shortcut must be performed) would not be given a tactical basis but well before starting the descent, together with the RTA. This would allow FMSs to plan and uninterruptedly execute CDOs from the top of descent (TOD) to the touchdown. During the negotiation process, the ATC must know with high accuracy the feasible RTA window for each aircraft and potential shortcut.

To implement this concept, a two-way communication is assumed between the aircraft crew and the ATC. Arriving aircraft would provide information about its feasible arrival time window, and ATC would assign specific combination of tromboning short-cut (or route) and also a RTA to a given metering fix (typically the approach intermediate fix). This thesis focuses on defining all available routes and quantifying their ATW for a realistic tromboning procedure published for Frankfurt airport.

Arrival time windows are defined as a time difference between earliest and latest times of arrival. Different types of arrival will be considered in this study:

- CDO and non-CDO (where intermediate short level flights are allowed);
- powered descents (with an engine power and speed-brake usage unrestricted) and energy-neutral descents (with engines at idle and no speed-brakes usage thorought the descent); and
- fuel optimal descents (for benchmarking purposes).

Besides defining time windows, a distance sensitivity analysis is also performed. This reflects the importance of communication between aircraft and ATC, to be as early as possible. All results are presented in Chapter 4 in form of tables and figures with some discussions. These results are obtained after three steps, which represent the first three chapters of the thesis:

- First – “Scope and literature reviews”. Here we review works done by other scientists and based on that we set path for ours.
- Second – “Simulation system setup”. Where particular airport and its STAR of interest is chosen. Other parameters and boundaries chosen and defined.
- Third – “Experimental setup”. Applied software and its basics are presented. Input files and their architecture is defined.

Chapter 1 SCOPE AND LITERATURE REVIEW

1.1. Scope of the thesis

Airport surroundings and in particular the Terminal Maneuvering Area (TMA) is a complex system that consists of a large number arrival and departure routes that interferes between them. In order to understand it and be able to control the air traffic flow it should be separated in particular routes for investigation.

The purpose of this thesis is to combine shortcuts of a tromboning arrival with assignment of RTAs and investigate the variety of the ATW that could be obtained. By using advantages of tromboning routing for full extent we will aim to show that RTA can be extended. As a result- all approaching aircrafts would know their remaining distance allowing proper descend planning for CDOs that would reduce a workload for the flight crews and ATC interference with vectoring would be avoided.

In this work, Frankfurt Main airport's STAR PSA25N will be investigated. Investigate in this context stands for determination of all possible tromboning short-cuts and their earliest and latest times of arrival with energy-neutral (neither thrust nor speed brake use all along the descent) and powered (with allowed use of thrust and speed brakes) types of descend while following CDO and non-CDO profiles.

Beside the determining approach time window additionally optimization distance sensitivity analysis and fuel optimal approach time window will be investigated taking following limitations or assumptions in to account:

- Only one aircraft type is simulated;
- realistic weather conditions are not considered (calm wind and standard atmosphere conditions considered);
- a simplified dynamic model is simulated (point-mass model);
- RTA window computation from a single aircraft point of view (no surrounding traffic considered); and
- RTA window assumes no uncertainty (i.e. the autopilot can perfectly guide the aircraft to satisfy the RTA).

Thesis statement: To achieve an efficient sequencing and merging in an airport its extreme RTA limits have to be identified first.

1.2. Literature review

ATM has a high interest between scientific communities as it has a wide area where new technologies and management principles could be applied. Number of different approaches for ATM in terminal area are reviewed in this chapter.

"CDOs are one type of OPD where a predefined procedure with a static routing is followed by the arriving aircraft and in which the aircraft maintains a near-idle throttle setting from TOD to a point with in several miles from the threshold" [4]. Although some scientists would not agree with a statement about a static routing [5].

Only CDO procedures by itself does not satisfy nowadays requirements for heavy congested airports. For that purpose, RTA procedures were developed and became a key of NextGen and SESAR programs. Although RTA is not a complete solution but merely a tool to assist in managing the increasing complexity of air traffic system [6].

Starting from the basics we should mention Cao [4], who compared fuel consumption of non-CDO and CDO. Beside the significant fuel savings achieved by CDO, he concluded that there exists only a single fuel optimal profile (least fuel required), and proposed to use en route segment for an approach time controllability. Similar idea to use en route speed adjustments, linear holdings was mentioned by Smedt [6]. Who identified that it could cause an issue to an ATC handling traffic in previously overflown sectors. Just mentioned researches presents the basics of RTA operation principles as it is continuous descent flight meeting the required time of arrival at some prescribed point.

Different ways of RTA implementation were proposed by some researchers:

Takeichi *et al.* [5] presented "Tailored Approach" concept with a fixed TOD point. Additional path segments were added (Radius-to-fix and Track-to-fix), extending or shortening the route to meet RTA. Such type of approach is beneficial against fixed way point routing as it has higher approach time controllability.

Smedt *et al.* [6] investigated actual data from Melbourne International Airport and applied the RTA principles with modified sequence (different landing sequence than in a base line case). It reduced ATC workload, NM flown and fuel consumed. But it was efficient up to particular traffic density, above which ATC intervention was required using vectoring, holding procedures. To improve capacity of RTA with modified sequence an earlier descent was proposed as flight time increase with decreasing TAS with an altitude. Although no evaluation of earlier descent side effects was discussed.

The same limitation was met by Park *et al.* [7], who noticed that CDO is limited to low traffic hours, as it is difficult to maintain separation between different types of aircraft. In this context it is interesting to mention another research accomplished by Park [8], where he proves the existence of common feasible time range for all types of aircraft in a CDO.

In contradiction to previously discussed papers, Takeichi [9] did not face previously mentioned RTA with CDO capacity limitations

Several common issues/questions are noticeable in reviewed papers about implementation of CDO:

- How heavy an aircraft should be considered? Does it have an impact on a CDO performance? Should the weight changes (fuel usage) be taken into account?

In most of reviewed papers aircraft weight is chosen without any explanation [5, 3, 8], while in others historical data is analyzed. Park *et al.* [11] in his paper used historical data to obtain seven different weight cases for a particular aircraft type: minimum, maximum, $\pm 2\sigma$, $\pm 1\sigma$ and average weight.

Importance of different factors for flight performance is presented [8, 9] after sensitivity analysis. Results concluded that most of factors, like environmental, aircraft or flight deck, has little or no influence to the results. Two main exceptions were weight and wind that can lead in extreme height errors [10].

The influence to the feasible time is obvious as “the minimum feasible time limit (earliest arrival), which is lower bound from the performance point of view, is increased monotonically as descent weight increased. On the other hand, the maximum feasible time limit (latest arrival), which is upper bound of the time performance, is not increased monotonically and there exists a peak descent weight in which the upper bound has maximum value” [11].

Although the weight has a significant impact on a performance, none of the reviewed sources consider weight changes during the descent due to fuel usage. Some justify such decision with a fact that less than 2% of total fuel is consumed during descent [6], others that the fuel usage for descent is very small fraction of total mass and the influence can be neglected [12].

- What is the maximum time window that could be achieved? Could the RTA be changed after TOD?

Feasible time calculation could be done in two slightly different ways [8]. First option it is a time between minimum time and minimum fuel flight time [11]. Second it is between minimum and maximum flight time. The second way is useful to assess performance bounds (maximum size windows), but in a real life first option might be preferable by the airlines. As minimum fuel and maximum time profiles does not coincide, using maximum time profile would lead in to over burning fuel and wasting aircraft operating time that makes important fraction of total operating cost. But it is worth to note that 80% wider time window can be achieved by using the second way [8].

Simulations have shown that an aircraft that has already started CDOA, idle power and using only energy modulation through elevator control, can manage its arrival at the

Initial Approach Fix (IAF) within 4 minutes time window [12]. It shows that a RTA can be changed after the TOD. In addition, the earlier the RTA instructions were received, the wider RTA time range would be achieved [9]. RTA updates made at 20.000ft altitude gives up to +-200sec. time window, while changes at 8.000ft – only +-7.6 sec. controllability. Side effects of such controllability are discussed as well [10].

Just mentioned controllability is defined as a time by which the flight might be delayed or advanced to be at a metering point compare to its initial ETA. Flight trajectory that has a mean flight time is regarded as the flight with an optimal arrival time controllability, as an aircraft has widest capability to extend or reduce flight time.

- Can an optimal profile be flown in basic Vertical Navigation (VNAV) modes?

The suboptimal profile proposed consisting of four phases that can be flown with VNAV functions [11]. First and fourth phases (as defined in [11]) could be chosen between constant flight path angle and constant rate of descent (ROD), as in these stages acceleration or deceleration may be required depending on RTA. Second phase of the trajectory is also generated with a constant ROD to capture the CAS acceleration. The third phase is determined to constant CAS for descent on one of the CAS boundary as required for minimum time or minimum fuel case. Discussed trajectory seems to be more theoretical than close to the real ones as there are no Mach phases used for high altitude flights and no usual ATM limitations.

The same authors in their other paper [7] implemented local limitations and proposed improved profile consisting of: constant Mach - constant CAS - constant ROD- constant CAS 250kt below 10.000ft - constant flight path angle to satisfy the final point conditions. Beside the proposed profile they concluded that current algorithm used by FMS is more than 20 years old and could be improved for higher accuracy.

The above reviewed papers set a foundation for this Ms. Thesis. Some authors even stated in their conclusions that route length variations could be used to extend feasible time for the RTA procedure and it is worth to investigate it: “It would be interesting to compare the energy- neutral RTA window with that achievable by using path lengthening or stretching even though pilots would probably prefer energy modulation to reduce workload and increase situation awareness.” [12].

Chapter 2 SIMULATION SYSTEM SETUP

2.1. Dynamo

Dynamo – an in-house trajectory optimization software developed by the ICARUS research group of UPC is the main tool for this research.

The Dynamo provides fast results for trajectory optimization and trajectory prediction problems of different kind and complexity. Together with a simulation environment, these serve the purpose of evaluating current Air Traffic Management (ATM) paradigm structure and procedures, along with proposing enhancements for a more sustainable future [13].The following paragraphs explain what stands behind the Dynamo software.

Trajectory optimizer requires the definition of a mathematical model describing the aircraft dynamics along with a model for certain atmospheric variables. In this thesis, the dynamics of the aircraft expressed by the following set of non-linear ordinary differential equations, where aircraft is presented as a point-mass and wind effects are neglected:

$$\frac{dv}{dt} = \dot{v} = \frac{T-D}{m} - g\sin\gamma \tag{2.1}$$

$$\frac{ds}{dt} = \dot{s} = v\cos\gamma \tag{2.2}$$

$$\frac{dh}{dt} = \dot{h} = v\sin\gamma \tag{2.3}$$

The state vector **x**=[v,s,h] is composed, respectively, by the true airspeed(TAS), the distance to go and the altitude. The mass of the aircraft is considered as constant. *D* and *T* are aerodynamic drag and thrust; *FF* is the fuel flow and *g* the gravity acceleration.

The control vector **u**=[γ,π,β] is composed of the aerodynamic flight path angle, throttle settings and speed-brakes deflection, respectively.

ISA atmospheric model is considered, where density, pressure and temperature are dependent on the altitude. In the thesis the following normalizations are used:

$$\delta = \frac{p}{p_0}; \quad \theta = \frac{\tau}{\tau_0}; \quad \sigma = \frac{p}{p_0}; \tag{2.4}$$

It is assumed that the throttle linearly controls T between the idle and maximum thrust setting (T_{idle} and T_{max}, respectively), which are functions of θ, δ and Mach number M:

$$T = T_{idle} + \pi(T_{max} - T_{idle}), \;\; \pi \in \{0,1\} \tag{2.5}$$

The aerodynamic drag is modeled as:

$$D = \frac{1}{2}\rho S v^2 C_D \qquad \textbf{(2.6)}$$

Where S is the wing area and C_D is the drag coefficient, a function of the lift coefficient C_L, M and β. The expression for C_L is obtained by assuming continuous equilibrium (i.e. the vertical component of the lift force balances the weight):

$$C_L = \frac{2mg}{\rho S v^2}\cos\gamma \qquad \textbf{(2.7)}$$

Finally, the fuel flow *FF_idle* is modeled as a function of M and θ, δ and the nominal fuel flow FF as a function of M, the normalized thrust T⁄δ and θ. Although the mass is considered to be constant, the fuel flow is computed in order to obtain fuel consumption figures

Optimization of an aircraft trajectory formulated as a multi-phase constrained optimal control problem, in which it is desired to determine the control history of the aircraft **u**(t) during either fixed or variable time interval [t_0,t_f] such that a given cost function **J**(**u**(t),**x**(t),p) is minimized or maximized while satisfying a set constraint function **c**(**u**(t)**x**(t),p)≤0 and certain bounds on the state, control and non-time dependent parameter p.

Direct collocation methods have been used that transforms the original continuous optimal control problem into a non-linear programing (NLP) optimization problem. The time histories of control and state variables are discretized at a set collocation points, being the system of ODEs defined by Eq.(2.1)-(2.3) approximated by some continuous function over each collocation step. The values of these discretized variables, along with some non-time dependent parameters, become the unknowns of the new finite variable problem, which can be formally as a NLP problem and solved by standard NLP solvers [14]. Therefore, direct methods require an efficient algorithm to solve the NLP, which may include hundreds or thousands of variables and constraints. Trapezoidal collocation method is applied as it shows a good trade-off between accuracy and execution time needed to solve highly constrained NLP problems [2].

2.1.1. Aircraft

Airbus A320 alike model was used for the simulations and was present together with the software. The aircraft performance model (i.e. fuel flow, drag coefficient, maximum and minimum thrust functions) is based on an accurate performance data from manufacturer. These data are obtained as results of experimental tests and specific tabular form [2].

2.1.2. Profile

Profile files were designed on previously discussed model. Profiles contains multiple descent stages between the optimization initiation point and landing phase. Landing phase contains few stages for an aircraft configuration changes that were not an object for optimization and were fixed for all runs. Reason for that was because metering fix was selected just before the landing phase being at FAP.

In total 4 profile files were written with slight differences required for the case. These 4 profiles can be divided in to two groups- powered and energy-neutral. Each of them contain profile for a CDO and a non-CDO.

All profiles start with accelerated/ decelerated cruise phase. Usage of thrust is allowed even in neutral case and flight could be accelerated or decelerated in cruise flight before it would start descend.

Descend in energy-neutral profiles were restricted by enforcing idle thrust and forbidding speed-brake usage. The only adjustment required between energy-neutral profiles was setting minimum ROD of 500ft/min for CDO to avoid although short but constant level flights for the faster deceleration.

To get powered profiles, energy-neutral profiles were modified. Initially only thrust and speed-brakes usage limitation was removed. That led to unexpected and operationally not acceptable behavior when aiming for the latest arrival. As there were no altitude limitations- aircraft started descend straight after ERMEL and shortly reached altitude of 5000ft. That was more than hundred nautical miles away from the threshold. Results were great for the scientific reasons, but that could not be operationally justified. Flying at 5000ft for prolonged period requires enormous amount of fuel and noise nuisance. If such delay were required, it would make much more sense to use an air holdings.

To avoid such behavior two altitude limitations were implemented. First altitude limitation was used from the STAR chart: to be over way point PSA at or above FL130. Originally limitation is to be over PSA at FL130 because currently crew does not know how many track miles they can expect. Less restrictive option was chosen as by our scenario crew would be informed in advance about the routing. Second limitation was based on the distance. Descend was restricted to FL100 before 40NM from the threshold.

Figure 2.1 shows one phase of the descend profile. As it can be seen it contains speed (Mach and CAS), altitude, distance (or way point as in this case), flight path angle (FPA) limitations, thrust and speed brake usage boundaries.

```xml
<phase id="ALT_PSA_lim"> <!--altitude limit- not below
    <nodes>60</nodes>
    <config>CLEAN</config>
    <engine>climb</engine>

    <eventconstraints>
        <initial>
            <constraint>
                <type>ALTITUDE</type>
                <nominal>13000</nominal>
                <lower>13000</lower>
            </constraint>
            <constraint>
                <type>WAYPOINT</type>
                <lower>PSA</lower>
            </constraint>
        </initial>
    </eventconstraints>

    <pathconstraints>
        <constraint>
            <type>THRUST</type>
            <nominal>0</nominal>
            <upper>100</upper>
            <lower>0</lower>
        </constraint>
        <constraint>
            <type>FPA</type>
            <upper>0</upper>
            <lower>-6</lower>
        </constraint>
        <constraint>
            <type>HDOT</type>
            <upper>-00.0</upper>
        </constraint>
        <constraint>
            <type>CAS</type>
            <upper>350</upper>
            <lower>200</lower>
        </constraint>
        <constraint>
            <type>SPEEDBRAKE</type>
            <upper>100</upper>
            <lower>0</lower>
        </constraint>
        <constraint>
            <type>MACH</type>
            <nominal>0.72</nominal>
            <upper>0.82</upper>
            <lower>0.20</lower>
        </constraint>
    </pathconstraints>
```

Figure 2.1 part of profile xml-formatted definition file used in Dynamo

2.1.3. Route

As it was previously mentioned, 17 different routes were generated from the PSA25N arrival. The same number of route files were created. Each containing all the waypoints for an appropriate route. Beside the waypoint name, its coordinates and bank angel limitation is defined. All files were named as “route#.xml” where # is the number of route. An example of waypoint structure in the route definition file is given in figure 2.2.

```
<WPT>
    <bank>30.0</bank>
    <name>ERMEL</name>
    <lat>49.189167</lat>
    <lon>11.043611</lon>
</WPT>
```

Figure 2.2 part of route17.xml file, a xml-formatted definition file used in Dynamo

2.2. Batch script

Batch processing is the execution of series of jobs in a program on a computer without any manual intervention. One of the main advantage is automation and good computer resources usage while a disadvantage is that it cannot be terminated once it is launched.

The batch script was written to eliminate huge amount of manual work that would have been required to run and collect required data from each simulation manually. Script contains number of commands and their task is to:

- create a folders to store results and simulation data
- create text document with headings that would later be used to store required data
- run “for” cycle for 17 times as 17 different route configurations were used. Main simulation parameters as CD)/non-CDO, neutral/powered are set here
- check feasibility of the solution
- extract required data from the simulation and store in a previously created text document
- store all simulation data in defined folders.

Although Batch script is capable to run all requires simulations at once, lower level of automation was chosen. Script is set so that for different scenario parameters (type of descend, usage of power and speed-brakes) have to be adjusted in a “for” loop. Such choice was made to be able to rerun simulations for the particular scenario if adjustments or improvements would be required for the profile or route.

Full script can be seen in Appendix A.

Chapter 3 EXPERIMENTAL SETUP

3.1. Aircraft

An Airbus A320 was chosen for the simulations as it is one of the most common type of aircraft. All the simulations were executed assuming a 90% of the maximum landing mass (MLW), which roughly corresponds to 58 tons. As in most cases near idle descend was expected, the assumption that weight will not change during descend was done.

3.2. Meteorological conditions

International Standard Atmosphere (ISA) was considered with a local atmospheric pressure adjusted to seal level (QNH) of 1013hp and no winds along the route.

3.3. Route

The airport of study is Frankfurt/ Main (IATA: FRA, ICAO: EDDF) in Germany. We concentrated on PSA 25N STAR. That is used by the traffic approaching from South to land in FRA on a 25R (right) runway. Transition from en route flight to STAR starts at Spessart (PSA) NDB and terminates at point DF422. DF422 is an intermediate fix for ILS (instrumental landing system) Y 25R. It is the point where an aircraft is established on a final approach track. That is followed by final approach fix, where the ILS glide slope is intercepted.

PSA 25N STAR is of tromboning type (see Fig. 1.1). The main feature of trombining arrival is flying in parallel to the final approach track on a downwind (as between points DF411 and DF416) or even upwind (as between points DF407 and DF 408). It allows ATC with a shortcut or just with two vectors (normally 90 degree turns) shorten the route/ flight time as required for the sequence and set traffic on the final approach track (see figure 3.2). Nowadays airplane proceeding on tromboning type arrival is unable to follow CDO as remaining distance is never known until establishing on final approach track. Because of that reason, aircraft start descending earlier to be ready for any shortcut. During rush hours when no shortcut is available due to sequencing it leads into low level flights with high fuel consumption and bigger noise footprint.

In this work we assume that exact routing is known for the Flight Management System (FMS) before the Top of Descent (TOD). We defined that turn might be initiated only when being over one of the published waypoints. By applying such assumption, we can get a finite number of possible and known routes that would be impossible otherwise.

Additionally, three more route points were created between DF407 and DF408. Points were named as VP1, VP2 and VP3, they are located perpendicular to DF412, DF413 and DF414. By using improved route tromboning procedure could be used to the full extent. Hypothetical TMA boundary was set so that it would start before the reaching first point of STAR. ERMEL point was chosen for that purpose (figure 3.3). This leads to a total 17 different routing options shown in table 3.1.

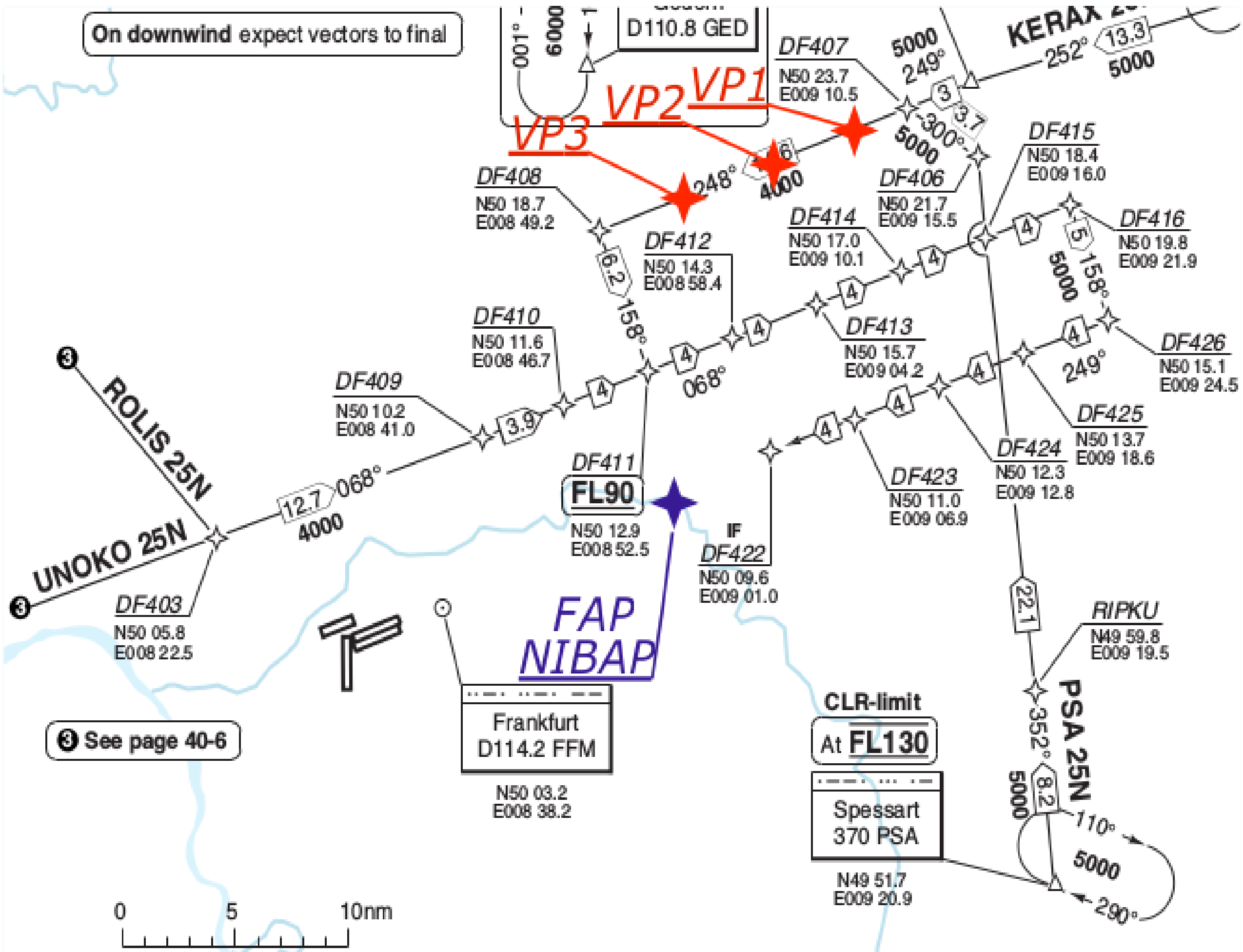


***Figure 3.1**. FMS/GPS RNAV 25R tromboning (source: German AIP)*

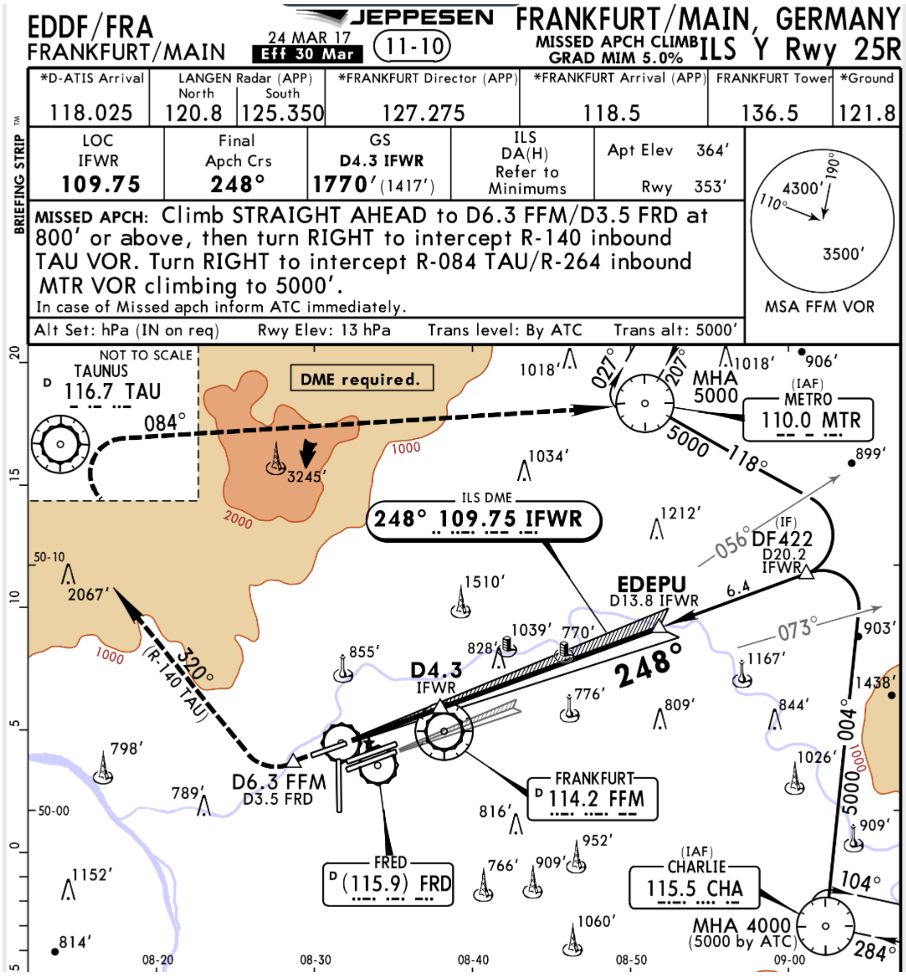


Figure 3.2 ILS Y 25R

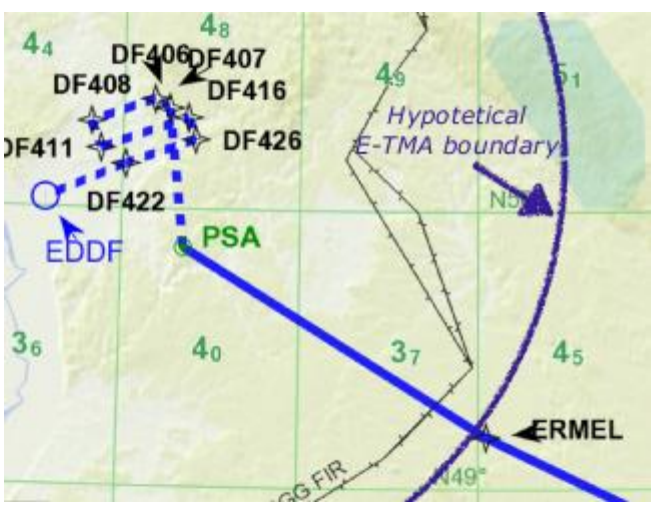


Figure 3.3 Hypothetical TMA boundary

Table 3.1 PSA25N routing options

Route ID	Waypoints sequence	Remaining distance [NM]
01	ERMEL-PSA-...-DF422	204
02	ERMEL-PSA-...-VP3-DF412-...-DF422	194
03	ERMEL-PSA-...-VP2-DF413-...-DF422	186
04	ERMEL-PSA-...-VP1-DF414-...-DF422	180
05	ERMEL-PSA-...-DF415-DF425-...-DF422	197
06	ERMEL-PSA-...-DF414-DF424-...-DF422	190
07	ERMEL-PSA-...-DF413-DF423-...-DF422	183
08	ERMEL-PSA-...-DF412-DF422	175
09	ERMEL-PSA-...-VP3-DF412-...-DF415-DF425-...-DF422	187
10	ERMEL-PSA-...-VP3-DF412-DF413-DF414-DF424-DF423-DF422	180
11	ERMEL-PSA-...-VP3-DF412-DF413-DF423-DF422	173
12	ERMEL-PSA-...-VP3-DF412-DF422	168
13	ERMEL-PSA-...-VP2-DF413-DF414-DF415-DF425-...-DF422	179
14	ERMEL-PSA-...-VP2-DF413-DF414-DF424-DF423-DF422	172
15	ERMEL-PSA-...-VP2-DF413-DF423-DF422	168
16	ERMEL-PSA-...-VP1-DF414-DF415-DF425-...-DF422	172
17	ERMEL-PSA-...-VP1-DF414-DF424-DF423-DF422	168

All flights were started 20NM before ERMEL. It was assumed that at that point the FMS would contact with ATC by using datalink to start the negotiation of the route and RTA. FMS would upload its computed feasible RTA window and would receive instructions from the ATC with required time of arrival and routing.

Till the point ERMEL aircraft would keep its initial speed and FL. After passing ERMEL it could follow optimized profile for the given routing to satisfy RTA.

In order to assess the sensitivity of the time window to the remaining distance available when the negotiation is performed, the powered earliest and latest times of arrival for each route have been computed for two additional cases, modifying the distance at which the aircraft crosses the E-TMA boundary. For the first case it is assumed that the boundary is located 20NM behind ERMEL, for the second case it is located 20NM ahead.

3.4. Vertical profile

Vertical profiles were designed based on recommendations, data and limitations provided in Airbus A320 Flight Crew Operating Manual (FCOM).

Vertical profiles (altitude and speed) were designed based on the vertical profile shown in a figure 1.3. It shows current FMS profile versus FMS profile with DPO (Descend Profile Optimization) function. Improved profile updates FMS performance data base by reducing margins in descent model. We pushed it even further by removing the speed margin.

An aircraft would start descend with constant Mach till crossover altitude (figure 1.4). After initial Mach becomes equal to predefined CAS it would continue with constant CAS.

Depending on airspace class it has a speed limitation of 250kt below FL100. That gives third, flatter phase of descend with deceleration to CAS below 250kt. After the limitation is met, an aircraft would continue with constant CAS down to an altitude from which it would decelerate to the speed appropriate for landing phase initiation/ configuration changes.

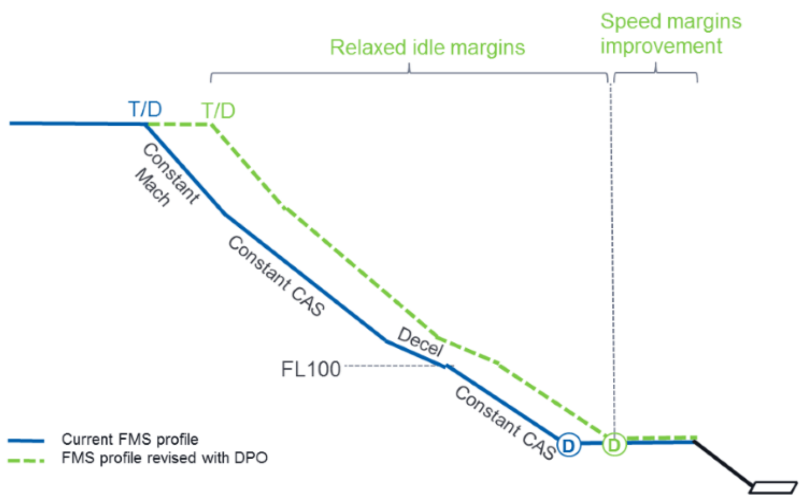


Figure 3.4 Typical descent speed profile
(Source: https://services.airbus.com/upgrade/environment/fuel-efficiency/descent-profile-optimisation-dpo)

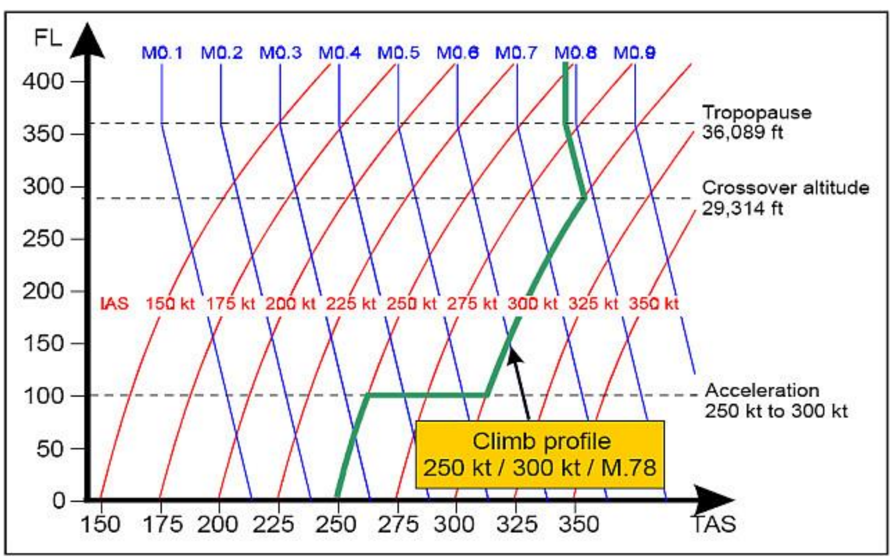


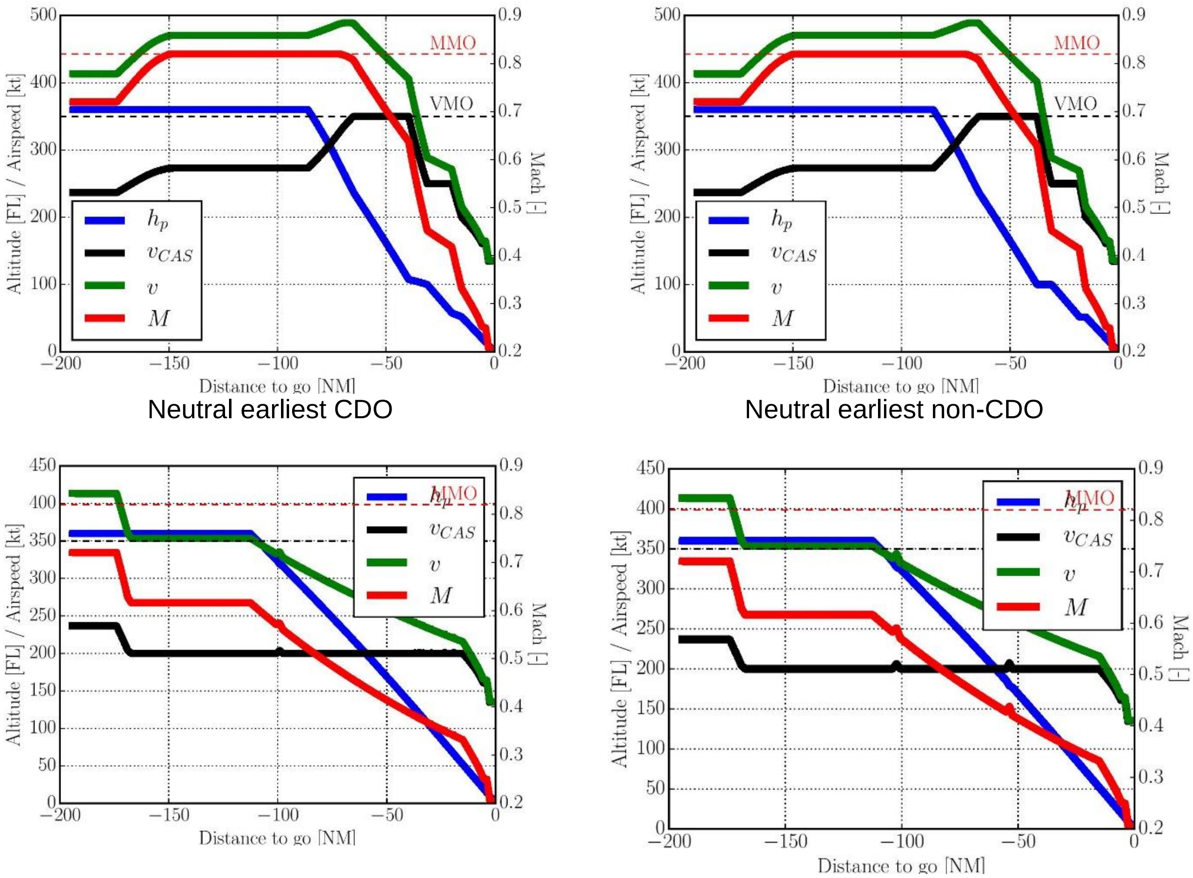
Figure 3.5 Crossover altitudes

Chapter 4 RESULTS

A total of 238 simulations were performed that covers 10 different scenarios (CDO/non-CDO; neutral/powered etc.) with 17 different routes each.

4.1. Neutral profiles

Energy-neutral descent profiles are displayed in figure 4.1. We can see that after an aircraft passes the point from which the RTA and route negotiation starts, speed is adjusted accordingly to the predefined arrival target (earliest of latest).



Neutral earliest CDO

Neutral earliest non-CDO

Neutral latest CDO

Neutral latest non-CDO

Figure 4.1 Vertical and speed profiles of the energy-neutral descents

The TOD depends on the arrival target speed. The TOD has no difference between latest arrivals (latest CDO and latest non-CDO). It can be explained by the fact that from TOD aircraft flies with minimum clean speed and no decelerations are required. As no decelerations required- no intermediate cruise phase for a non-CDO.

Cruise and descent in an earliest case is flown at a maximum Mach and CAS. High speed requires decelerations before reaching FL100 with a lower speed constraint. A slight difference in a distance of TOD between earliest cases is obtained due to different types of deceleration before FL100 and before intercepting the glide slope at the FAP. Non-CDOA reaches its TOD later as decelerations can be done in a constant level flight, with less time and distance required. Longer cruise- shorter approach gives better results, shorter flight time.

Table 4.1 shows the gain/benefit that might be obtained from the non-CDO operations in energy-neutral cases. As already discussed, there is a small benefit of it while aiming for the latest arrival, up to 1.5s. (0.0222 min). Slightly higher benefit might be obtained in earliest case, up to 7s. (0.111min). These few seconds leads in slight increase in fuel consumption. Up to 0.3% (2kg) extra fuel consumed for an earliest case and negligible amount for the latest case. Both time and fuel consumption difference among earliest and latest CDO and non-CDO cases are constant and there is no route distance influence

Table 4.1 Comparison between energy-neutral CDO and non-CDO flight times

Route	Time saving in a non-CDO earliest case (s)	Neutral Earliest non-CDO (min)	Neutral Earliest CDO (min)	Neutral Latest CDO (min)	Neutral Latest non-CDO (min)	Extra time in non-CDO latest case (s)
1	6.67	31.966	32.077	41.752	41.757	0.30
2	6.67	30.669	30.780	40.022	40.024	0.12
3	6.67	29.741	29.852	38.791	38.794	0.24
4	6.67	28.884	28.995	37.644	37.667	1.32
5	6.67	31.069	31.180	40.556	40.553	-0.18
6	6.67	30.163	30.274	39.349	39.359	0.60
7	6.67	29.247	29.358	38.130	38.148	1.14
8	6.67	28.323	28.434	36.906	36.914	0.42
9	6.67	29.774	29.885	38.836	38.850	0.78
10	6.67	28.865	28.976	37.621	37.640	1.14
11	6.67	27.997	28.108	36.472	36.487	0.90
12	6.67	27.347	27.458	35.606	35.620	0.84
13	6.67	28.839	28.950	37.592	37.589	-0.18
14	6.67	27.949	28.060	36.401	36.422	1.32
15	6.67	27.373	27.483	35.640	35.649	0.60
16	6.67	27.959	28.070	36.416	36.434	0.30
17	6.67	27.452	27.563	35.739	35.752	0.12

The earliest and latest arrivals of neutral CDO are 27min 28s (27.458 min) and 41min 45s (41.752 min) obtained respectively in a shortest and longest routes. All the rest results are just intermediate solutions showing time limits of the respective route. Time widow can be extended from 14min 17s to 14min 24s in non-CDO.

4.2. Powered profiles

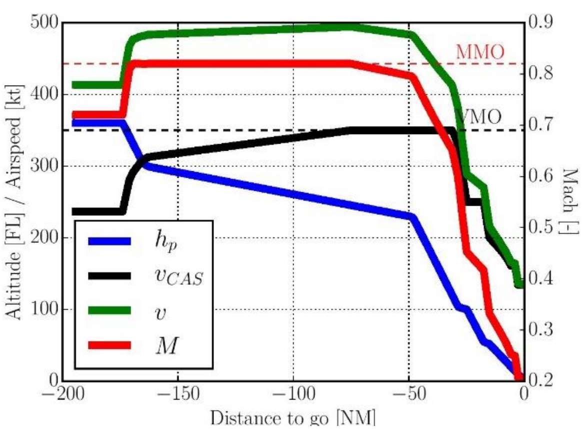
Powered approach profile is very different from the previously discussed energy-neutral profile. During Powered approach aircraft starts its descent straight after passing the point from which flight optimization is initiated. Same behavior is in both earliest and latest cases. It might be explained by using speed versus altitude chart (Figure 3.5).

When aiming for the shorter flight time and being at higher altitude, the limiting speed of sound(MMO) is lower than limiting CAS(VMO) so an aircraft will be limited by the Mach number. At low altitudes, the speed of sound is high so an aircraft is limited by the CAS.

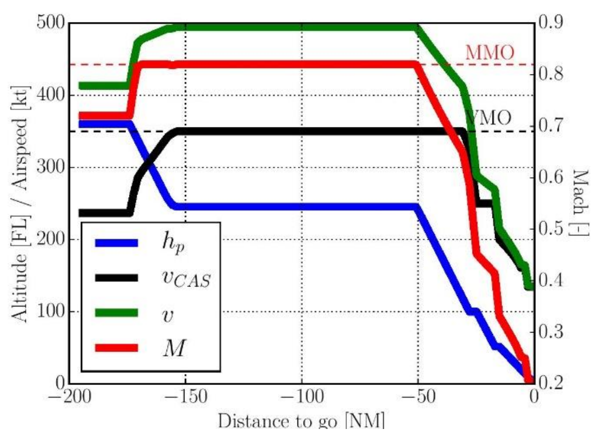
When aiming for the shortest flight time aircraft would fly towards upper limit of their speed, so at some point they will have to switch from remaining under Mach limit to remaining under the CAS limit.

When aiming for the longest flight time- CAS will set the lower speed limit through all decent. If top speed limit (MMO/VMO) is set to avoid transonic regions around the hull, the lower limit is set to avoid stalling an aircraft. Both limits have additional safety margins to compensate for unexpected occurrences and uncertainties.

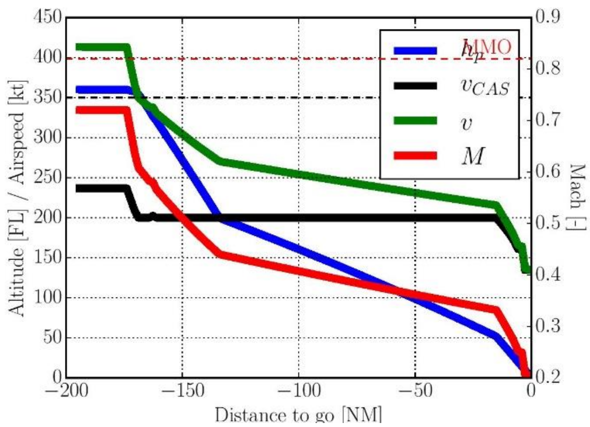
During CDO, earliest case after initial steep descend aircraft continues with a shallow descent (min ROD) to be near crossover altitude as long as possible. While in a non-CDO- after initial steep descend aircraft cruise at crossover altitude till the point from which it has to continue descend. As well figure 3.5 shows that the highest TAS can be obtained at a crossover altitude.



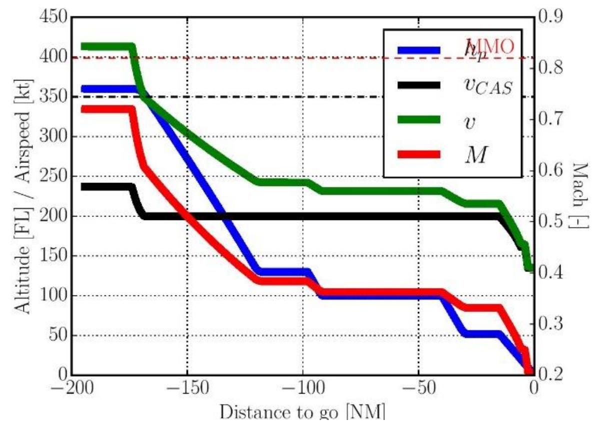
Powered earliest CDO



Powered earliest non-CDO



Powered latest CDO



Powered latest non-CDO

Figure 4.2 Vertical and speed profiles of the powered descents for route number 2.

The remaining part of the approach is similar to the corresponding energy-neutral approaches, just it is steeper as speed-brakes usage is allowed. Speed-brakes are deployed to decrease the total energy of the aircraft.

Powered latest CDO starts with a steep descend down to an altitude from which it could continue to the FAP with a minimum ROD of 500 ft/min allowed by the CDO profile. As previously explained such constraint was enforced to avoid undesired level flights. While non-CDO initially goes down to the first limiting altitude(FL130 until reaching PSA) and then continues with an intermediate cruise phases at the restricted altitude along the route until it can continue down to the other limiting altitude(FL100 until 40NM) where it continues intermediate cruise. Low level flying for the latest arrival can also be explained by using figure 3.5. Where we can see that TAS decrease with decreasing altitude while keeping constant IAS/CAS.

Table 4.2 Comparison between Powered CDO and non-CDO flight times

Route	Route length (NM)	Time saving in non-CDO earliest case (s)	Powered earliest non-CDO (min)	Powered earliest CDO (min)	Powered latest CDO (min)	Powered latest non-CDO (min)	Extra time in latest non-CDO case (s)
1	204.361	12.54	30.376	30.585	47.671	49.115	86.64
2	194.188	10.68	29.142	29.320	45.440	46.476	62.16
3	186.911	9.54	28.259	28.418	43.811	44.594	47.04
4	180.189	8.52	27.443	27.585	42.286	42.852	34.02

5	197.322	11.22	29.523	29.710	46.134	47.288	69.24
6	190.221	10.08	28.661	28.829	44.554	45.452	53.88
7	183.036	8.94	27.789	27.937	42.936	43.587	39.00
8	175.795	7.92	26.909	27.041	41.274	41.709	26.16
9	187.170	9.54	28.290	28.449	43.872	44.662	47.40
10	180.046	8.46	27.426	27.567	42.253	42.816	33.78
11	173.236	7.62	26.599	26.725	40.679	41.047	22.08
12	168.140	6.90	25.980	26.095	39.449	39.731	16.92
13	179.839	8.46	27.401	27.541	42.206	42.762	33.36
14	172.860	7.50	26.553	26.678	40.591	40.954	21.78
15	168.339	6.90	26.004	26.120	39.497	39.782	17.10
16	172.939	12.54	26.563	26.688	40.606	40.970	86.64
17	168.961	10.68	26.080	26.197	39.653	39.937	62.16

Comparing CDO and non-CDO flight times (table .4.2) we can see that non-CDO approach can provide us with 12s. (0.209 min) earlier and 86s. (1.444 min) later arrival. The main difference that we get in comparison between energy-neutral and powered arrivals is that time gain has direct relation to the route length. Longer route implies higher gain. Additional time gained in a non-CDO has a price of 145kg of extra fuel in latest and 73kg in earliest case.

The earliest and latest arrivals of powered CDO is 26min 06s (26.095 min) and 47min 40 (47.671 min). Time window is 21min 36s. It might be extended up to 23min 08s by flying non-CDO profile.

Comparing energy-neutral with powered CDOs we can see that ~50% wider approach time window can be obtained (figure 4.3). It has its price as it might be seen in figure 4.7 where the fuel usage are displayed for a comparison.

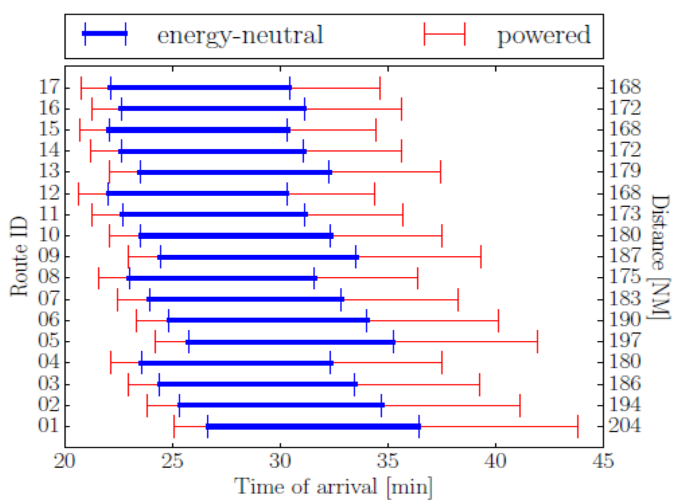


Figure 4.3 Comparison of the time window for energy-neutral and powered CDOs

4.3. Sensitivity analysis to initial condition

For the Powered approaches we noticed that route length has an influence on the results. This suggested to make a distance sensitivity analysis, adding two different waypoints along the route: One 20NM before and one 20NM after the waypoint ERMEL.

Only powered and CDO types were used for analysis. Energy-neutral approaches were out of interest as results were easily predictable. As descend profile is identical for each route and TOD is always at the same distance from the threshold. Optimized route length variation would have a minor influence for the energy-neutral approach as only cruise might be accelerated or decelerated for a 20NM longer or shorter period.

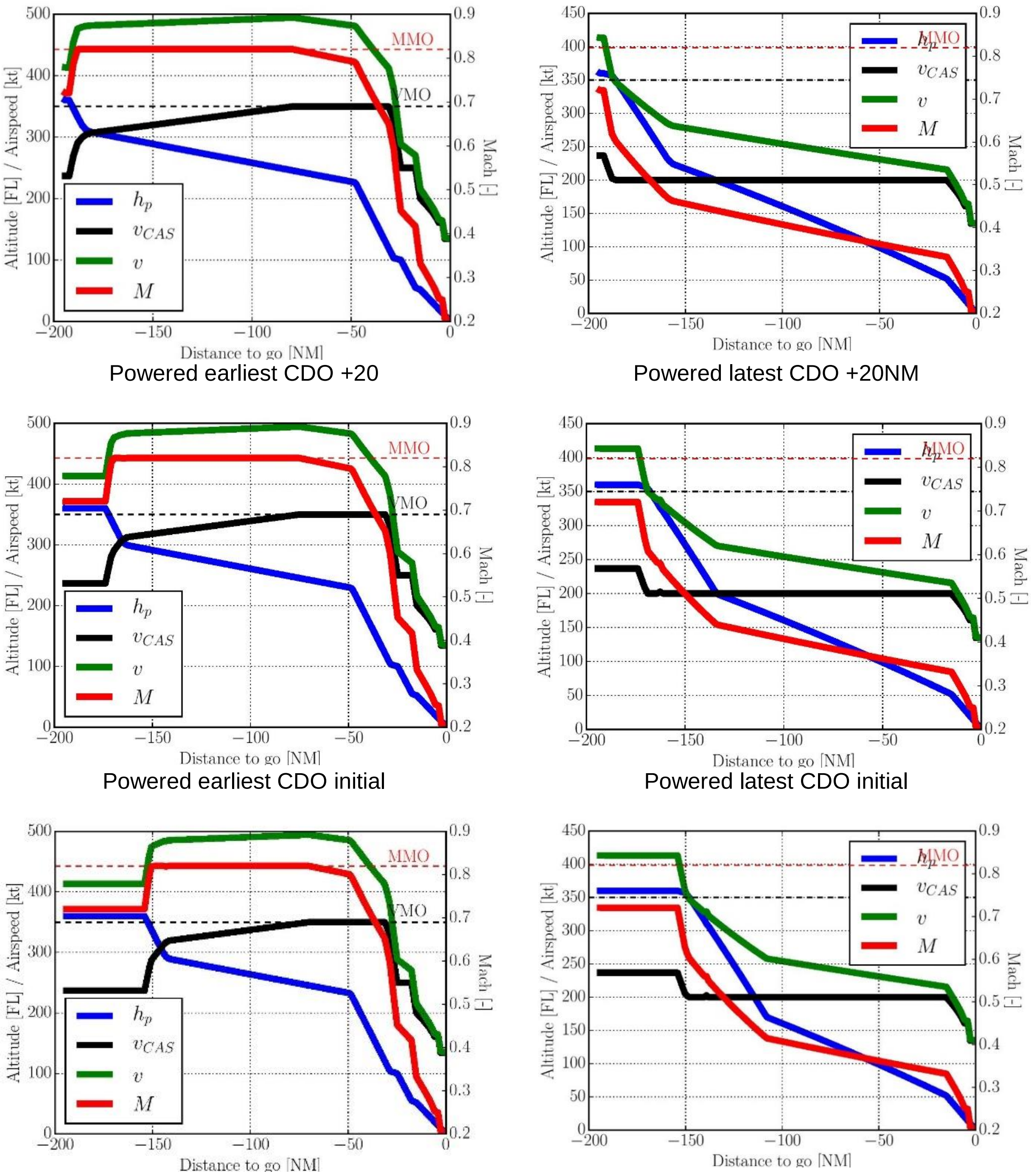
Results revealed that initial part of the Powered optimized flight was used to compensate for changes in optimized route length. It was common for all runs. The final part of approaches remained unchanged.

Earlier and shorter initial steep descent gave a benefit of longer flight at altitudes close to the crossover altitude in +20NM earliest arrival case. While in -20NM route- lower initial steep descent was used to compensate for the shorter optimized flight route. That led in a shorter portion of flight with the highest speed. Similar behavior is observed in the latest cases. Just this time low level flight is the most beneficial one.

Table 4.3 ±20NM earliest arrival comparison

Route	Time saved in -20NM case (s)	Fuel saved in -20NM case (kg)	Initial flight time (min)	Initially fuel used (kg)	time saved in +20NM case (s)	Fuel saved in +20NM case (kg)
1	-24.60	42.71	30.57	1,017.16	22.20	-12.58
2	-25.20	23.30	29.30	948.90	22.80	-12.00
3	-25.20	34.52	28.40	908.37	22.80	-18.35
4	-25.80	37.41	27.57	866.28	23.40	-16.62
5	-25.20	26.84	29.69	979.94	22.80	-10.76
6	-25.20	55.44	28.81	941.75	22.80	-4.96
7	-25.80	33.71	27.92	880.51	23.40	-18.14
8	-25.80	31.68	27.02	821.70	23.40	-38.92
9	-25.80	51.23	28.43	928.58	22.80	-0.34
10	-25.80	20.32	27.55	847.20	23.40	-47.97
11	-25.80	42.70	26.71	817.87	23.40	-31.54
12	-26.40	36.62	26.08	781.39	23.40	-33.16
13	-25.80	39.36	27.52	849.98	23.40	-35.07
14	-25.80	32.82	26.66	805.31	23.40	-29.94
15	-26.40	32.49	26.10	772.62	23.40	-47.43
16	-24.60	22.38	26.67	789.86	22.20	-48.42

17	-25.20	32.97	26.18	775.63	22.80	-36.60



Powered earliest CDO +20

Powered latest CDO +20NM

Powered earliest CDO initial

Powered latest CDO initial

Powered earliest CDO -20NM

Powered latest CDO -20NM

Figure 4.4 Vertical and speed profiles of the powered CDO with different initial conditions and route number 2

Table 4.4 ±20 latest arrival comparison

Route number	extra time in -20 NM case (s)	fuel saved in – 20NM case (kg)	Initial flight time (min)	initially fuel used (kg)	extra time in +20NM case (s)	fuel saved in +20NM case (kg)
1	-90.60	15.08	47.65	857.29	73.20	-14.36
2	-97.20	22.00	45.42	800.23	79.20	-9.01
3	-101.40	24.26	43.79	755.51	83.40	-25.53
4	-106.20	23.03	42.27	708.77	87.00	-21.62
5	-94.80	19.80	46.12	817.94	77.40	-15.81
6	-99.60	20.11	44.54	772.40	81.00	-17.33
7	-104.40	17.86	42.92	730.12	84.60	-16.04
8	-109.20	21.72	41.26	682.88	88.80	-19.45
9	-101.40	27.88	43.86	765.61	82.80	0.86
10	-106.20	28.18	42.24	716.92	87.00	-6.84
11	-111.00	32.58	40.66	677.03	90.60	-9.65
12	-112.80	22.72	39.43	635.17	92.40	-24.06
13	-106.80	29.57	42.19	714.03	87.00	-19.68
14	-111.60	21.35	40.57	665.47	91.20	-23.33
15	-112.80	27.30	39.48	641.09	92.40	-20.63
16	-90.60	16.60	40.59	662.79	73.20	-28.40
17	-97.20	22.36	39.64	639.61	79.20	-28.96

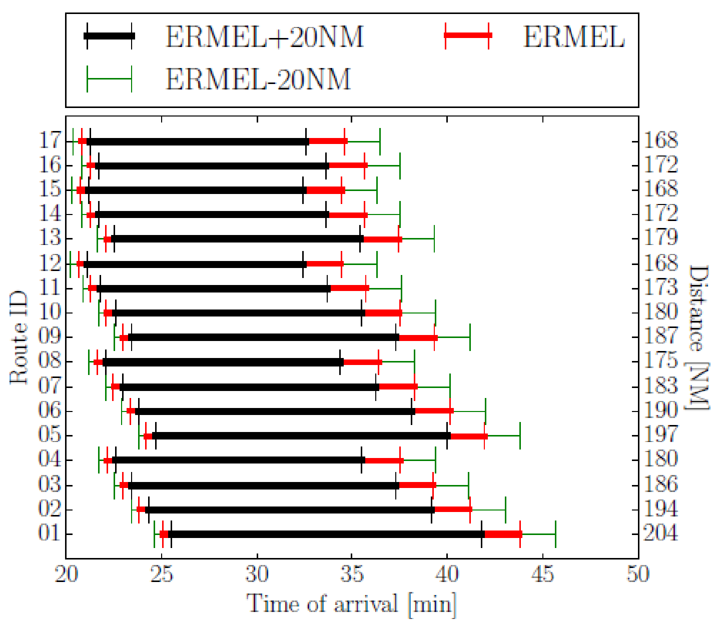


Figure 4.5 Time window sensitivity to distance for the powered CDOs.

Figure 4.4 shows that earliest arrivals are less sensitive to the distance variations compare to the latest. It might be explained by the fact that 20NM route length variation in the latest case is used for the flight with 160kt lower speed (TAS/GS as no wind conditions are assumed) compare to the initial. While in the earliest case only 90kt difference between initial condition and speed used for those additional (or subtracted) 20NM in optimized conditions.

Time window of initial flights (optimization started from ERMEL point) was 21 min 36sec (21.6 min), -20NM case – 19 min 39 sec (19.65 min), +20NM case – 23 min 13 sec (23.21 min). Collected data revealed that any increase in optimized distance gives wider approach time window but requires additional fuel. Vice versa in case of shorten optimized distance.

Simulations shows that satisfying time constraint or aiming for a wider approach time window could be done by adjusting the position of the TOD. But it would require additional fuel consumption. Current findings impelled us to find out the fuel optimal profiles. Such profiles are getting more and more interesting to the operators as fuel price is rising and its usage makes the main component of their operating expenses.

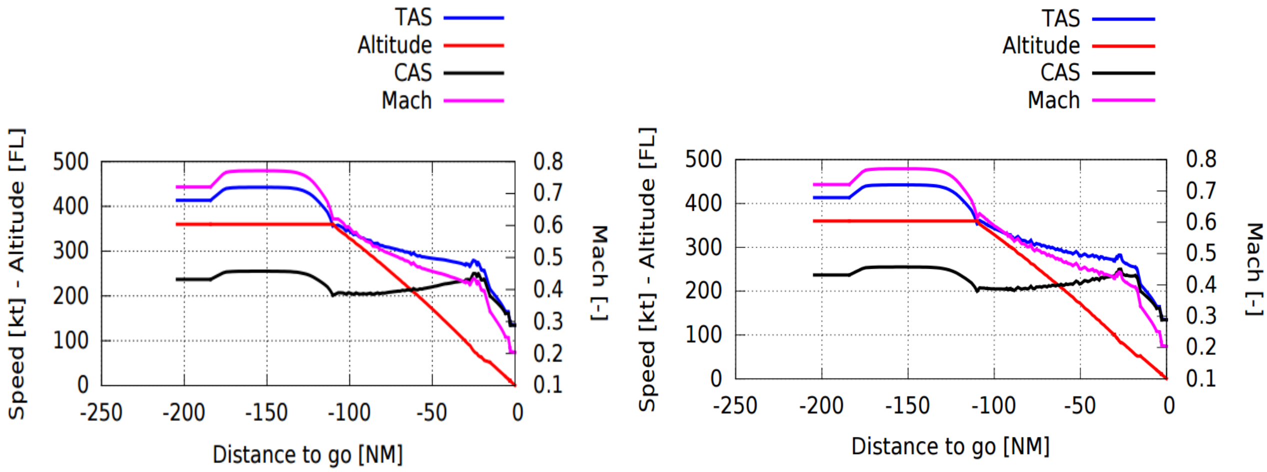
4.4. Optimum fuel approaches

Two simulations were performed to find fuel optimal solutions. CDO and non-CDO profiles were investigated. Both came up with the same solution. As we can see from the comparison in table 10, time and fuel consumption difference is negligible.

Capability of intermediate level off in non-CDO had no influence on optimal fuel profile. Minimum fuel usage was achieved by using continuous descend with speed close to minimum drag speed/ best glide speed (green dot speed).

Approach time window can be set for the fuel optimal profiles as well. As descend profiles for all the runs was identical- it is based just on the cruise length. Time window of 4min. 53sec. (293 sec.) was achieved between longest and shortest routes. That falls in between the previously discussed time frames with almost twice less fuel consumed (fuel optimal approaches requires between 396 and 573kg) figure 4.7.

Current profiles are the most similar to the ones that are used by the airlines. As intention is to keep cruise flight as long as possible and descend without any intermediate level flights unless required for speed reduction.



Fuel optimal CDO approach

Fuel optimal non-CDO approach

Figure 4.6 Vertical profiles of the fuel optimal approach procedure

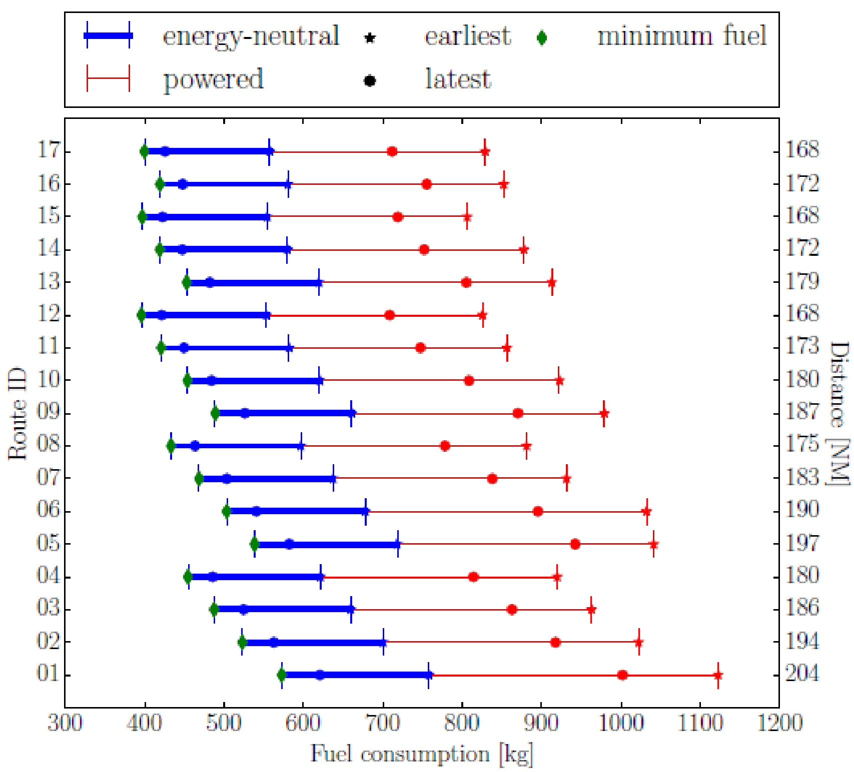


Figure 4.7 Fuel consumption for the different trajectories

Table 4.5 Comparison between CDO and non-CDO fuel optimal profiles

Route	Flight time optimal CDO (min)	Fuel optimal CDO (kg)	Flight time difference between CDO and non-CDO (s)	Fuel difference (kg)	Flight time optimal non-CDO (min)	Fuel optimal non-CDO (kg)
1	37.80	572.95	0.58	0.18	37.81	572.77
2	36.48	523.11	-4.51	-0.03	36.41	523.15
3	35.50	487.61	-3.10	-0.02	35.45	487.62
4	34.55	455.01	1.98	0.22	34.58	454.80
5	36.85	538.63	-3.00	-0.01	36.80	538.64
6	35.86	504.15	3.59	0.48	35.92	503.67
7	34.88	469.13	3.22	0.52	34.94	468.61
8	33.92	433.65	1.50	0.31	33.95	433.34
9	35.45	489.20	-1.20	0.08	35.43	489.12
10	34.48	454.45	2.67	0.32	34.52	454.13
11	33.58	421.26	1.75	0.32	33.61	420.94
12	33.22	396.09	-16.70	0.06	32.94	396.03
13	34.53	453.29	-2.35	0.18	34.49	453.11
14	33.52	419.41	-0.10	0.18	33.52	419.24
15	33.17	397.42	-15.36	0.26	32.92	397.16
16	37.80	419.53	-2.22	0.08	37.81	419.45
17	36.48	400.40	-15.84	0.36	36.41	400.04

Chapter 5 CONCLUSIONS

This thesis presented a new option for the Air Traffic Controllers (ATC) to better handle the traffic in congested Terminal Maneuvering Areas (TMAs). The concept, based on 4D trajectories, uses the required time of arrival (RTA) functionality, combined with a tromboning arrival concept. Introduction of tromboning arrival allows significantly widen the feasible time window at a given metering fix without requiring any interference from the ATC, such as path stretching (radar vectoring. Moreover, it reduces workload for ATC and also aircraft crew and allows for the on-board Flight Management System (FMS) to be in the loop regarding the remaining distance to the runway threshold. This remaining distance is vital when aiming for the environmental friendly procedures, such as continuous descent operations (CDO).

The simulations performed in this Thesis revealed that using all the variety of routes and following CDO without using neither engine thrust nor speed-brakes (energy-neutral CDO), a time window of 14min 17 s might be obtained. This window could be increased by almost 50% (up to 21min 36 s) by allowing engine thrust and speed brakes to be used. Further analysis on the fuel consumption associated with the time windows uphold the belief that the RTA selected by the ATC will have a very significant impact on the flight efficiency and in the environmental impact. In addition to the CDO, non-CDO were simulated that gave even wider approach time window (ATW) that requires additional fuel.

Approach time window importance is obvious and as required wide of it might change with the day time (rush hours) or weekdays (working days/weekend) optimized flight distance influence on ATW analysis performed. Data revealed that earlier instructions could be beneficial although it is not directly dependent.

ATW is the most important for the ATC while its cost is vital for the operators. Fuel and time are two and the only components of the operating cost for an airlines. Fuel optimal profiles calculated and presented. It revealed that an ATW of more than 4 minutes might be obtained by using different tromboning arrival routes with fuel optimal descend profile.

Fuel analysis just confirmed that currently used technique to stay at cruise altitude as long as practicable is based on fuel efficiency. As cruise flight gives the best rate of NM/kg fuel.

It is worth noting that the results of this Thesis lead to a conference publication [2]. Finally, the following areas are open for further discussion and could be a guidepost for the next steps in this research:

- In the thesis assumption was used that turns might be initiated just over published waypoints. That gave a finite number of possible routes. By giving a freedom to turn whenever convenient/required, more different length routes could be obtained. Although all the new routes (with turns not necessary over the waypoint) would fall in between the previously discussed ones. An advantage could be that new arrival times would fall in between the ones discussed in the thesis and would give meter continuity of the ATW. No wind (calm wind) scenario was used for the simulations. Different wind scenarios or historical data could be used to analyze the sensitivity of the feasible time window.

- Wind forecast not always match with the real condition. Analysis of what impact could this mismatch have and what corrections (additional thrust or speed brake) it could require could be very interesting area for the future works.
- Lindsay [10] proposed slightly different method to calculate an ATW. According to his methodology- time window should be calculated between minimum time and optimum/minimum fuel profiles as an area falling in between minimum fuel and maximum flight time is operationally harmful. ATW calculation could be even more advanced by taking into account other components of operational cost, like aircraft leasing cost, crew work time, maintenance. Cost index (CI) based ATW could be simulated in future works to get it more realistic and acceptable for operations.

References

[1] IATA, “New IATA Passenger Forecast Reveals Fast-Growing Markets of the Future”, Press release no. 57. 16 October 2014.

[2] Ramon Dalmau, Justinas Alekna and Xavier Prats, “Combining the assignment of pre-defined routes and RTAs to sequence and merge arrival traffic”, in Proceedings of the 17th Aviation Technology, Integration, and Operations Conference (ATIO). AIAA. Denver (Colorado), USA., 2017

[3] Adrian Pawelek, Piotr Lichota, Ramon Dalmau and Xavier Prats “Arrival traffic synchronisation with Required Time of Arrivals for fuel-efficient trajectòries” In proceedings of the 17th Aviation Technology, Integration, and Operations Conference (ATIO). AIAA. Denver (Colorado), USA., 2017

[4] Yi Cao, Li Jin, Nguyen V. P. Nguyen, Steven Landry, Dengfeng Sun and Joseph Post, “Evaluation of Fuel Benefits Depending on Continuous Descent Approach Procedures”, Air Traffic Control Quarterly, Vol. 22, No. 3 , pp. 251-275, 2014.

[5] Noboru Takeichi and Daigo Inami, ”Arrival-Time Controllability of Tailored Arrival Subjected to Flight-Path Constraints”, Journal of aircraft Vol. 47, No. 6, November–December 2010.

[6] David De Smedt, Jesper Bronsvoort and Greg McDonald, “Controlled Time of Arrival Feasibility Analysis”, in Proceedings of the Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013). FAA/Eurocontrol. Chicago (Illinois), USA, 2013.

[7] Sang Gyun Park and John-Paul Clarke, “Optimal Control Based Vertical Trajectory Determination for Continuous Descent Arrival Procedures”, Journal of Aircraft. January, Vol. 52, No. 5, pp. 1469-1480. 2015.

[8] Sang Gyun Park and John-Paul Clarke, “Feasible Time Range Analysis of Wide Fleet for Continuous Descent Arrival” in Proceedings of the Aviation Technology, Integration, and Operations Conference (ATIO). AIAA. 2013.

[9] Noboru Takeichi, Takao Hatano and Yutaka Fukuda, “Continuous Descent Trajectory with Optimum Arrival Time Controllability” Proceedings of the 28th International Congress of the Aeronautical Sciences (ICAS). 2012.

[10] Peter A. Lindsay, Colin Ramsay, Miguel Vilaplana, Javier Lopez Leones, Enrique Casado and Paul C. Parks, “Robustness of Idle-throttle Continuous Descent

Approach Trajectories against Modified Timing Requirements” in Proceedings of the 9th Aviation Technology, Integration, and Operations Conference (ATIO). AIAA. 2009.

[11] Sang Gyun Park and John-Paul Clarke, “Fixed RTA fuel optimal profile descent based on analysis of trajectory performance bound” Journal of Guidance, Control, and Dynamics, Vol. 30, No. 5 , pp. 1319-1330. 2007.

[12] Ramon Dalmau, Xavier Prats, “Controlled time of arrival windows for already initiated energy-neutral continuous descent operations” Transportation Research Part C – Emergent Technologies. No 85. pp. 334-347. 2017.

[13] R. Dalmau, M. Melgosa, S. Vilardaga, and X. Prats, “A fast and flexible aircraft trajectory predictor and optimiser for atm research applications,” in *7th SESAR innovation days*, Belgrade, Serbia, 2017

[14] Ronald Verhoeven, Ramon Dalmau, Xavier Prats ane Nico de Gelder, “Real-Time Aircraft Continues Descent trajectory Optimization With ATC Time Constraints Using Direct Collocation Methods”, Proceedings of the 30th International Congress of the Aeronautical Sciences (ICAS). September 2014.

Appendix A Batch script

```
# make changes in here for case folders, profile and knobs_neutral <cost> 3/4

cd
cd /media/justinas/Data/Dynamo


# mkdir -p results_Neutral_earliest
# mkdir -p results_Neutral_latest
# mkdir -p results_Powered_earliest
 mkdir -p results_Powered_latest_nonCDA

# cd results_Neutral_earliest
# cd results_Neutral_latest
# cd results_Powered_earliest
 cd results_Powered_latest_nonCDA
logdir=$PWD


# #!! comment the following lines if not first iterations
 : > summary.dat #this and next one
 echo Route Nr. Solver_status Model_status NM init_time FAF_time THR_time init_to_FAF optimised_time init_to_THR
FAF_to_THR FUEL TAS_at_10000 CAS_at_10000 Dist_at_10000 TAS_at_TOD CAS_at_TOD Distance_of_TOD >> $logdir/summary.dat
 mkdir -p listing
 mkdir -p output
 mkdir -p results
 mkdir -p log
 # rm ./listing/*   #<--
 # rm ./output/*    #<--
 # rm ./results/*   #<--
 # rm ./log/*       #<-- ctrl /

cd

cd Documents/Software/dynamo/dynamo_v1/Data/Scenario
mkdir -p results
cd results
currdir=$PWD

cd ..
cd ..
cd ..
cd build

# ??? cat $currdir/input/scenario_tmp.xml | sed s?currdir?$currdir?g > $currdir/input/scenario.xml
echo ""
echo ""
echo "================ ROUTES ======="
for route in $(seq 1 17); do    #16384


           cat    ../Data/Scenario/scenario_neutral_batch_tmp.xml    |    sed    s/ROUTE/Route${route}/g        >
../Data/Scenario/scenario_neutral_batch.xml

          cp -a ../Data/Scenario/PSA25N/Route${route}.xml ../Data/Scenario/
```

```
           #./dynamo --scenario=../Data/Scenario/scenario_neutral_batch --profile=profil --aircraft=A320 --log=2 --
route=Route${route}
                  #Neutral profile CDA
           #./dynamo  --scenario=../Data/Scenario/scenario_neutral_batch  --profile=profilnonCDA  --aircraft=A320  --
log=2 --route=Route${route}
                  #Neutral profile non CDA
           # ./dynamo --scenario=../Data/Scenario/scenario_neutral_batch --aircraft=A320 --profile=TSprof --log=2 --
route=Route${route}
                   #Powered profile CDA
            ./dynamo --scenario=../Data/Scenario/scenario_neutral_batch --aircraft=A320 --profile=TSnoCDA --log=2 --
route=Route${route}
                   #Powered profile non CDA

          rm ../Data/Scenario/Route${route}.xml


 STATUS=`cat $currdir/O_listing.lst | grep "MODEL STATUS" | awk 'END{print $4}'`
 MOD_STATUS=$STATUS
# to make changes for output path in scenario file
            if [ "$STATUS" -eq "2" ]; then
                STATUS="Optimal Solution"
            elif [ "$STATUS" -eq "7" ]; then
                STATUS="Feasible Solution"
            elif [ "$STATUS" -eq "8" ]; then
                STATUS="Integer Solution"
            else
                STATUS="infeasible"  # 5 - localy infeasible
            fi
echo Route $route
echo $STATUS

SOL_STATUS=`cat $currdir/O_listing.lst | grep "SOLVER STATUS" | awk 'END{print $4}'`
 # Solver status 1 - normal completion

  T=2
  TO=36000
  TOD=${TO/.*}
  ch=36000
  check=${ch/.*}
  while [ "$TOD" -eq "36000" ]; do
  TS=$((T+1))
  T=$TS
  TO=`cat $currdir/O_result.dat | grep "Phase" -A $T | awk 'END{print $6}'`
  TOD=${TO/.*}
   if [ "$T" -eq "41" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "82" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "123" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "184" ]; then
   TB=$((T+1))
   T=$TB
```

```
 TOD=36000
 fi
 if [ "$T" -eq "245" ]; then
 TB=$((T+1))
 T=$TB
 TOD=36000
 fi
 if [ "$T" -eq "306" ]; then
 TB=$((T+1))
 T=$TB
 TOD=36000
 fi
done
#echo $T

 TT=$((T-1))
 T=$TT
 TOD_DI=`cat $currdir/0_result.dat | grep "Phase" -A $T  | awk 'END{print $5}'`
 TOD_TAS=`cat $currdir/0_result.dat | grep "Phase" -A $T | awk 'END{print $7}'`
 TOD_CAS=`cat $currdir/0_result.dat | grep "Phase" -A $T | awk 'END{print $11}'`
 D=0
 TOD_DIS=`echo $D - $TOD_DI |bc`
 # echo TOD distance $TOD_DIS
 # echo TOD TAS $TOD_TAS
 # echo TOD CAS $TOD_CAS

 INITIAL=`cat $currdir/0_result.dat | grep "init" | awk '(NR==1){print $4}'`

  FINAL=`cat $currdir/0_result.dat | grep "FAF" | awk 'END{print $4}'`

#echo init at: $INITIAL
#echo FAF at: $FINAL
TIME=`echo $FINAL- $INITIAL |bc`
#echo between init and FAF: $TIME

THR=`cat $currdir/0_result.dat | grep "landing" | awk 'END{print $4}'`
THRTIME=`echo $THR- $INITIAL |bc`
echo total flight time: $THRTIME

FAF_THR=`echo $THR - $FINAL |bc`
echo from FAF to THR: $FAF_THR

FUEL=`cat $currdir/0_listing.lst | grep "PARAMETER fuel" | awk 'END{print $6}'`
echo fuel burnt: $FUEL

DIS=`cat $currdir/0_result.dat | grep "init" | awk '(NR==1){print $5}'`
D=0
DIST=`echo $D - $DIS |bc`
echo route distance in NM: $DIST

# TEN_SPEED=`cat $currdir/0_result.dat | grep "app_cas_from" | awk '(NR==1){print $7}'`
# echo speed at 10.000ft: $TEN_SPEED
# TEN_DIS=`cat $currdir/0_result.dat | grep "app_cas_from" | awk '(NR==1){print $5}'`
# TEN_DIST=`echo $D - $TEN_DIS |bc`
# echo 10.000ft crossed NM from THR: $TEN_DIST

T=2
T0=10000
TOD=${T0/.*}
ch=10000
check=${ch/.*}
```

```
  while [ "$TOD" -ge "10000" ]; do
  TS=$((T+1))
  T=$TS
  TO=`cat $currdir/0_result.dat | grep "Phase" -A $T | awk 'END{print $6}'`
  TOD=${TO/.*}
   if [ "$T" -eq "41" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "82" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "123" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "184" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "245" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
   if [ "$T" -eq "306" ]; then
   TB=$((T+1))
   T=$TB
   TOD=36000
   fi
  done
  # echo line where 10000ft were crossed $T

   TT=$((T-1))
   T=$TT
   TEN_DIS=`cat $currdir/0_result.dat | grep "Phase" -A $T  | awk 'END{print $5}'`
   TEN_TAS=`cat $currdir/0_result.dat | grep "Phase" -A $T | awk 'END{print $7}'`
   TEN_CAS=`cat $currdir/0_result.dat | grep "Phase" -A $T | awk 'END{print $11}'`
   D=0
   TEN_DIST=`echo $D - $TEN_DIS |bc`
   # echo distance where 1000ft were crossed $TEN_DIST
   # echo speed when crosing 10000ft $TEN_TAS
   # echo CAS at 10000ft $TEN_CAS



#zip $currdir/listing.zip  $currdir/0_listing.lst > /dev/null

 # T_0=`zcat $currdir/listing.zip | grep "VAR t_0" -A 4 | awk 'END{print $2}'`
 T_0=`cat $currdir/0_listing.lst | grep "VAR t_0" -A 4 | awk 'END{print $2}'`
  #echo from list $T_0


 # T_f=`zcat $currdir/listing.zip | grep "VAR time_f" | awk 'END{print $5}'`
 T_f=`cat $currdir/0_listing.lst | grep "VAR time_f" | awk 'END{print $5}'`
  #echo from list $T_f
```

```
  T_lst=`echo $T_f - $T_0 |bc`
  echo time form lst: $T_lst

 echo Route $route $SOL_STATUS $MOD_STATUS $DIST $INITIAL $FINAL $THR $TIME $T_lst $THRTIME $FAF_THR $FUEL $TEN_TAS
$TEN_CAS $TEN_DIST $TOD_TAS $TOD_CAS $TOD_DIS >> $logdir/summary.dat

# to zip and move files
# zip $currdir/output.zip  $currdir/0_output.dat > /dev/null
# zip -q $currdir/result.zip  $currdir/0_result.dat
# zip -q $currdir/solvertrack.zip  $currdir/0_solvertrack.log

# mv $currdir/listing.zip $logdir/listing/list{$route}
# mv $currdir/output.zip $logdir/output/out{$route}
# mv $currdir/result.zip $logdir/results/res{$route}
# mv $currdir/solvertrack.zip $logdir/log/log{$route}


mv $currdir/0_listing.lst $logdir/listing/list{$route}
mv $currdir/0_output.dat $logdir/output/out{$route}
mv $currdir/0_result.dat $logdir/results/res{$route}
mv $currdir/0_solvertrack.log $logdir/log/log{$route}




done

echo "================================================="
echo ""
echo ""
```