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EUROCONTROL EXPERIMENTAL CENTRE

**EFFECT OF AIRCRAFT TIME KEEPING ABILITY ON ARRIVAL TRAFFIC CONTROL
PERFORMANCE - PROBABILISTIC MODELLING
4D TRAJECTORY MANAGEMENT VALIDATION - MODELLING 2008**

EEC Technical/Scientific Report No. 2009-010

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Summary: Probabilistic modelling is used to investigate the air traffic control performance benefits of aircraft Flight Management Systems (FMS) respecting required times of arrival (RTA) at an initial approach fix (IAF ~10,000 feet) agreed in advance, typically before top of descent. The probability of a sequence of aircraft meeting all controlled time of arrival (CTA) tolerances ($\pm 30s$) is modelled mathematically for different: (a) arrival control horizon times up to 1 hour, (b) mixtures of RTA equipped and unequipped traffic, (c) traffic densities, and (d) RTA accuracy. Results indicate the probability of a CTA sequence being met is above 0.9 for all arrival control horizon times tested with 100% of aircraft equipped with RTA, but decreases with decreasing RTA equipage levels for arrival control horizon times greater than ten minutes. Increasing RTA accuracy (standard deviation) from $\pm 10s$ to $\pm 5s$ (50%) increases probability of CTA sequence conformance e.g. for average traffic density from 0.92 to 0.95 (3%) for 95% equipage and 20 minutes arrival control horizon time. The probability of bunching of two to four aircraft in a spacing slot of 90s at the TMA entry is reduced by at least a factor of ten when all aircraft are equipped with RTA compared to all aircraft unequipped. Extended arrival control horizon times enabled by RTA allow delay absorption by speed control instead of path-stretching resulting in fuel savings increasing (relative to a controller without an arrival manager) from 110 ± 10 kg at 15 minutes to 150 ± 25 kg at 70 minutes. These fuel savings are due to improved efficiency in absorbing airborne delay with longer arrival control horizon times. Fuel savings analysis by Airbus related to optimisation of vertical profile, better metering at IAF and more accurate Estimated Times of Arrival (ETA) are included in appendices.						

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LIST OF ABBREVIATIONS

ADS-C	Automatic Dependent Surveillance - Contract
AOC	Airline Operating Company
ATM	Air Traffic Management
AMAN	Arrival MANager
BADA	Base of Aircraft DATA
CAS	Calibrated Air Speed
CDA	Continuous Descent Approach
CPDLC	Controller Pilot Data Link Communication
CTA	Controlled Time of Arrival
CTO	Controlled Time Over
ECAC	European Civil Aviation Conference
E-OCVM	European – Operational Concept Validation Methodology
ETA	Estimated Time of Arrival
ETMA	Extended Terminal control Area
FAF	Final Approach Fix
FL	Flight Level
IAF	Initial Approach Fix
IAS	Indicated Air Speed
NM	Nautical Mile
P-RNAV	Precision aRea NAVigation
RNAV	aRea NAVigation
R/T	Radio Telephone
RTA	Required Time of Arrival
SESAR	Single European Sky ATM Research
STAR	Standard Terminal Arrival Route
TMA	TerMinal control Area

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1. INTRODUCTION

1.1. EXPERIMENTAL BACKGROUND AND CONTEXT

Studies on designing a more structured terminal control area (TMA) for merging traffic streams together [3], highlighted the importance of protecting the TMA from poorly synchronised streams of arrival traffic. The degree to which traffic streams are synchronised greatly determines the efficiency of the merging process. The lower the synchronisation the more chance of large bunches (several aircraft in the same time tolerance), delay and perhaps saturation and go-arounds. A proposed solution is to plan TMA entry times which aircraft respect accurately enough to ensure an acceptable level of synchronization for the merging process [5], [11], [18]. Recent research using Monte Carlo analysis for arrivals following 3D routes and air traffic control (ATC) speed instructions to Houston intercontinental airport in Texas, USA indicated that a tolerance of 30s at the entry to the TMA was sufficient to absorb delivery variance over all aircraft [12].

Entries to European TMAs typically vary between 10,000 and 25,000 feet so that synchronised TMA entry times agreed before top of descent should be controlled for a large portion of the descent. Accurate time control in descent is not easy for an air traffic controller or tools on the ground because of the lack of awareness of aircraft performance. Research indicates that absolute [8] and relative [2], [4], [14], [16] airborne time control are feasible and could bring benefits for ATC. Recent research at NASA involves building a prototype Flight Management System to investigate a combination of absolute and relative time control from the flight deck [1].

Many aircraft are equipped with flight management systems that offer the ability to arrive at a requested time [7]. In 2007, it was estimated that 28% of flights in the ECAC (European Civil Aviation Conference) region were equipped with a RTA function expected to control within 30s tolerance or less and 11% within 6s [19]. Aircraft manufacturers are working to improve these figures particularly for descent phases of flight and to ensure robustness to weather uncertainties.

The objective of this collaborative study between EUROCONTROL Experimental Centre and Airbus was to evaluate benefits of aircraft accurately controlling their own entry time in to the arrival terminal area. An accuracy of ± 10 s, 95% of the time, was assumed, based on a state of the art review [19]. Probabilistic models of aircraft arriving at several IAFs trying to respect a sequence of CTAs within ± 30 s [12] were developed. The arrival performance of RTA equipped aircraft was modelled using a normal distribution with a standard deviation of 5s. A similar model was developed for unequipped aircraft under ATC speed control. CTA sequence conformance and risk of bunching were the main model outputs.

In [11] a simple calculation for potential fuel benefits of using speed control instead of path stretching is suggested and in [12], a more detailed model is used for cost savings in US airspace. This study used data from London Heathrow arrival traffic and Airbus aircraft performance data to estimate fuel savings of speed control compared to path stretching to see if there was a trade-off with sequence conformance.

This report is the result of work carried out by EUROCONTROL Experimental Centre in conjunction with Airbus during 2008. The context of this study is validation of SESAR (Single European Sky ATM Research) 4-D trajectory management concepts based on Controlled Time of Arrival (CTA) constraints achieved via aircraft FMS (Flight Management System) RTA functionality. Airbus is currently investigating possible improvements in FMS RTA functionality and this collaborative study forms a part of the analysis of ATM requirements. In particular two aspects are addressed:

- i) Predictability: CTA sequence conformance (probability of meeting a sequence of CTAs) and saturation risk
 - probabilistic model of ATC and traffic flow
- ii) Performance: Fuel/time cost benefit
 - case studies

1.2. CONCEPT OVERVIEW

1.2.1. Concept

It is assumed that flights within the extended TMA arrival control horizon time (not those enroute to other destinations) should conform to agreed 4-D trajectories and therefore have to respect associated time constraints namely Controlled Times of Arrival (CTA) at IAF or FAF or runway threshold (>2014). CTAs are absolute time constraints associated with tolerances (slot widths) which must be satisfied with high degrees of confidence. CTA conformance is a critical performance characteristic for ATC. Associated metrics include the probability of CTA modification and the probability of CTA conformance achievement (if CTA is not modified). Both are dependent on the CTA tolerance and the arrival control horizon time at which the CTA constraint is set.

CTAs are determined by ATC (typically using an arrival manager tool). Such calculations might take into account downlinked aircraft ETAs as well as traffic flow, and weather conditions (possibly also aircraft RNAV capabilities). Furthermore CTAs should ideally be calculated to enable continuous descents. CTA constraints would be uplinked to suitably equipped aircraft as RTAs and then the aircraft FMS function would be expected to fly the aircraft so as to meet the RTA constraint.

In today's operations an air traffic controller merges arrival traffic streams into sequences by giving speed, heading and altitude instructions perhaps with the aid of a tool such as an arrival manager. The arrival control horizon time of an arrival manager tool could be typically 40 minutes from landing in Europe which may span several sectors. Problems identified with today's operation are:

- speed instructions would have to be coordinated between sectors, which is not formally the case today;
- air traffic controllers may have to communicate several speed instructions to many aircraft;
- accuracy of the arrival time control depends on air traffic controller availability;
- frequent changes in CTA sequence.

The scenario proposed to address the above issues (compatible with SESAR 4D trajectory concept of operations [9][18]) is as follows:

Once an aircraft is within an arrival control horizon time:

- ATC uplinks 3D route (STAR, vertical constraints), (CPDLC or voice);
- AOC uplinks wind/temperature on aircraft request (AOC);
- ATC uplinks CTA at merging point (CPDLC or voice);
- Aircraft downlinks 4D predicted trajectory (4D pseudo waypoints) (ADS-C) and follows it to arrive within CTA tolerance.

Note: downlinking 4D trajectory is not assumed for this study, only time at IAF.

1.2.2. Expected Benefits

1.2.2.1. Predictability

- Increasing CTA sequence conformance.
- Reducing risk of TMA saturation.

1.2.2.2. Efficiency

- Fuel consumption:
 - More optimal delay absorption due to extended arrival control horizon time and avoiding tactical ATC path stretching.
 - More optimal vertical profile due to avoiding tactical ATC speed and level instructions (see Appendix B).
 - More optimised trajectories in TMA (between IAF and runway) from better metering (see Appendix C).
 - Integration of aircraft preferred ETA into arrival manager tool (see Appendix D).

1.3. PURPOSE OF DOCUMENT

The purpose of this document is to quantitatively assess the following potential benefits (subset of 1.2.2) of using aircraft FMS RTA functionality to meet CTA constraints:

- i) Predictability
 - a. increased CTA sequence conformance
 - b. reduced risk of TMA saturation
- ii) Flight efficiency - better fuel consumption through more optimal delay absorption
- iii) Environmental impact (CO₂) – reduction in mass of CO₂ released in to atmosphere

These benefits are compared to a baseline of air traffic controllers using speed instructions aided by an arrival manager tool.

1.4. SCOPE AND STRUCTURE OF DOCUMENT

The targeted operational environment is extended TMA with arrival management supporting P-RNAV routes and Continuous Descent Approaches until the Initial Approach Fix (IAF). The document structure is based on the E-OCVM Validation Reporting Template for Experiment Level [10].

Chapter 2 summarises the experiment and strategy planning. Chapter 3 describes how the validation exercises were conducted. Experiment results are given in chapter 4. Chapter 5 analyses the experiment outcomes and chapter 6 contains conclusions and recommendations. Appendix A details the case study on fuel efficiency due to more optimal delay absorption. Appendices B to D are provided by Airbus. They describe the benefits of optimisation of vertical profile, better metering at merge point and a refined arrival manager tool estimated time of arrival due to aircraft predicted 4D trajectory.

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2. SUMMARY OF EXPERIMENTS AND STRATEGY PLANNING

2.1. EXPECTED EXPERIMENT OUTCOMES, OBJECTIVES AND HYPOTHESES

The objective of the model based experiments is to quantify the links between CTA tolerance and compliance levels (and the relationship with arrival control horizon time) and:

- performance characteristics of ATC operations in (Extended) TMA, e.g. flight efficiency, ATC throughput/capacity, environmental impact etc;
- ETA/RTA performance characteristics of the aircraft (possibly considering different performance classes, weather conditions and dependence on equipped aircraft population).

It is expected that improvements of arrival time accuracy allow higher arrival sequence conformance for a given arrival control horizon time. And it is expected that for a fixed sequence conformance requirement the sequence length and arrival control horizon time increases. Consequently arrival manager tool efficiency should improve in terms of predictability and aircraft speed control (using the FMS RTA function). This is expected to result in earlier action on aircraft speed control which should reduce the need for path stretching, improve vertical efficiency and consequently save fuel.

As defined in the original agreed project objectives, the following aspects are considered separately:

- Earlier action on aircraft speed control reduces the need for path stretching and globally allows more economic flight speeds. The resulting benefits are linked to increased arrival control horizon time originating from increased CTA sequence stability. The improved arrival manager tool efficiency addresses the extent to which a given airborne delay can be achieved in the most efficient way through speed reduction.
- Improved vertical efficiency is linked to improved RTA accuracy because it reduces need for starting descents early and thus avoids number and length of level offs at low altitude (see Appendix B by Airbus).

Table 2-1 summarises the hypotheses to be tested under the corresponding improvement areas of predictability and efficiency.

Table 2-1: Hypotheses for performance (predictability and efficiency)

System performance characteristic	Improvement area	ID	Hypothesis
Predictability	CTA sequence conformance	PC1	Probability CTA sequence met increases with increasing RTA equipage
		PC2	Probability CTA sequence met reduces gracefully with decreasing RTA accuracy
	Saturation risk	PS1	Probability of saturation less with RTA
Efficiency	Fuel consumption	EF1	Fuel savings greater for RTA than unequipped aircraft

2.2. CHOICE OF METRICS AND MEASUREMENTS

The following metrics for dependent variables are used:

Table 2-2: Metrics of dependent variables

Metric	Range
Probability CTA sequence conformance	[0.0, 1.0]
Probability of bunch	[0.0, 1.0]
Fuel savings per aircraft arrival	kg

2.3. CHOICE OF METHODS AND TECHNIQUES

2.3.1. State of the Art

Probabilistic modelling is considered a cost-effective means of performance and reliability evaluation of complex dynamic systems. It has been used in a wide range of studies within ATM from conflict detection to runway throughput optimisation [13]. Probabilistic modelling was chosen for this study because arrival traffic control is a particularly complex dynamic part of ATC. The results of this probabilistic modelling were then used in a case study with a real traffic sample to estimate cost benefits using aircraft fuel consumption data first from BADA and then refined with Airbus performance data.

2.3.2. CTA Sequence Conformance (Probabilistic Modelling)

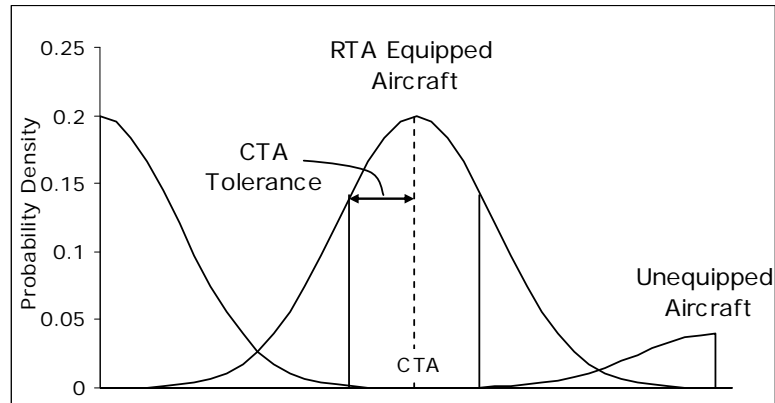


Figure 2-1: Normal probability density functions

It is assumed that a mixture of m aircraft unequipped with RTA and $n-m$ equipped with RTA are arriving at a TMA with several IAFs to meet a corresponding set of synchronised CTAs in anticipation of landing on the same single dedicated arrival runway. The distribution of traffic is assumed evenly spread and the number of IAFs sufficiently large such that separations are above the legal minima and the time keeping capability of each individual aircraft is independent of neighbouring aircraft. Therefore sequence conformance, the probability that a sequence of n aircraft all meet their CTAs (P_s) is assumed to be the product of the probabilities $P_u(i)$, that each unequipped aircraft i meets its own CTA in isolation and $P_e(j)$, that each equipped aircraft meets its own CTA in isolation (see equation 1).

$$P_s \approx \prod_{i=1}^m P_u(i) \prod_{j=m+1}^n P_e(j) \quad (1)$$

The impact of an aircraft failing to meet its CTA and the impact it might have on the sequence is not considered here. The probability of bunching is addressed in the next section. Probabilities of unequipped aircraft P_u and equipped aircraft P_e meeting their CTAs within tolerance of $\pm CTAT$ are modelled by normal distributions [15] (see equations 2 and 3).

$$P = \int_{-CTAT}^{CTAT} N(x) dx \quad (2)$$

$$N(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right) \quad (3)$$

Where the mean μ and standard deviation σ take values of μ_u and σ_u for unequipped aircraft and μ_e and σ_e for equipped aircraft respectively. The mean of the normal probability distribution is assumed to be the CTA. To model the short term uncertainty in aircraft position mainly due to wind, standard deviation for unequipped aircraft is assumed to increase linearly from 0 with arrival control horizon time up to 30 minutes and then remain constant at σ_u . The maximum σ_u corresponds to how well a controller can issue speed instructions to counter errors due to wind speed prediction at look ahead times greater than 30 minutes. The standard deviation for RTA equipped aircraft σ_e is assumed to be a constant 5s for any arrival control horizon time.

2.3.3. Saturation Risk Model

The following model uses traffic flow theory [6] to treat the TMA like a reservoir of aircraft. Assuming a TMA containing $n(t_0)$ aircraft at time t_0 , with incoming flow rate $f_{in}(t)$ and outgoing flow rate $f_{out}(t)$, then number of aircraft $n(t)$ at time t is given by:

$$n(t) = n(t_0) + \int_{t_0}^t (f_{in}(t) - f_{out}(t)) dt \tag{4}$$

For $0 \leq n(t) \leq n_{saturation}$

At saturation $n(t) = n_{saturation}$ and to avoid overload (more than safe limit of aircraft in TMA) the following condition should be respected $f_{in} \leq f_{out}$.

Assuming $n(t_0)$ is the nominal operating value $n_{nominal}$, and f_{in} and f_{out} have maximum values f_{inMax} and f_{outMax} then the minimum saturation time $t_{minSaturation}$ is given by:

$$t_{minSaturation} = \frac{n_{saturation} - n_{nominal}}{f_{inMax} - f_{outMax}} \tag{5}$$

Number of aircraft $k_{saturation}$ entering TMA during saturation time is given by:

$$k_{saturation} = f_{inMax} t_{minSaturation} \tag{6}$$

A measure for protecting TMA from overload is to ensure the probability $P_{ksaturation}$ of a bunch of aircraft greater than $k_{saturation}$ passing over the IAFs in a duration $t_{minSaturation}$ is very small.

Consider a sequence of similarly equipped aircraft with evenly spaced CTAs at the IAFs. The probability of a neighbouring aircraft arriving within tolerance $\pm CTAT$ of the same CTA can be estimated by considering the degree of overlap in normal probability distributions associated with each CTA. For example equation (7) gives the probability P_{bunch2} of either of the two nearest neighbours (infront and behind) arriving within a given aircraft's CTAT.

$$P_{bunch2} \approx 2 \int_{-CTAT}^{CTAT} N(x) dx \int_{Spacing-CTAT}^{Spacing+CTAT} N(y) dy \tag{7}$$

Where, Spacing is the time between CTAs at the IAF and the relative probability of a bunch of three occurring is assumed negligibly small. Similar expressions can be derived for bunches larger than two by considering the next but one nearest neighbours and so on.

2.3.4. Effects on Fuel Consumption (analytical case study: increase of arrival control horizon time)

Analytical case studies based on required probability of CTA sequence conformance with traffic from London Heathrow are performed for an arrival manager tool with different arrival control horizon times for different RTA equipage levels. These cases are compared to a baseline with no arrival manager tool.

The different arrival control horizon times are applied in an arrival manager tool context as follows: when an aircraft enters the arrival control horizon time then the arrival manager tool calculates a CTA/CTO (Controlled Time of Arrival/Over) and the RTA is set equal to that CTO. A CTO is an absolute time at a point; the CTO accuracy requirement is a time slot of ± 30 seconds.

The comparison is based on queue handling by an arrival manager tool, which assigns delays to arrivals when demand exceeds capacity. For each individual flight it addresses the extent to which a given airborne delay can be achieved in the most efficient way. But the benefit is averaged over all arrivals.

The comparison addresses the extent to which a given airborne delay can be achieved in the most efficient way through speed reduction. This comparison does not address the possibility that improved RTA precision leads to improved vertical flight efficiency.

2.4. SCENARIO SPECIFICATIONS

2.4.1. CTA Sequence Conformance

The scenario considered is aircraft arriving at one or several IAF(s) in preparation for landing in sequence on a single runway. The IAF marks the entrance to the TMA at typically 10,000 feet. The probabilistic model characteristics are:

Table 2-3: Arrival sequence conformance scenario parameters

Parameter	Units	Value
Uncertainty in arrival time of unequipped aircraft (standard deviation) at T minutes to go.	s	T (T < 30 minutes) 30 (T ≥ 30 minutes)
CTA tolerance size (CTAT)	s	±30

Routes are assumed to converge before or at a corresponding IAF and the number of routes can vary from as few as one or as many as the number of aircraft.

2.4.2. Saturation Risk

From fast time simulations performed at EEC involving a medium sized TMA with four IAFs feeding a dedicated arrivals runway with 90s minimum spacing, the following values were estimated by considering the capacities of longest and shortest possible route lengths: $n_{saturation} = 18$, $n_{nominal} = 15$, $f_{inmax} = 4$ aircraft in 90s and $f_{outmax} = 1$ aircraft in 90s. Using equation 4 and 5, a typical value for $t_{MINsaturation} = 90s$ and $k_{saturation} = 4$. For simplicity of calculation, a CTAT of half the average spacing is assumed $\pm 45s$, σ_u is 30s and σ_e is 10s.

2.4.3. Effects on Fuel Consumption (due to increase of arrival control horizon time)

The scenarios considered are based on the same airspace assumptions above with IAF at 10,000 feet and the vertical flight efficiency is considered equal for all cases:

- [1] Arrival manager tool (Baseline) - speed control through Controller via speed instructions. Arrival control horizon time = 15 minutes to IAF (typical of today's operations). RTA is not expected to bring substantial benefit because for arrival control horizon times less than 15 minutes, accuracies with and without RTA are comparable, and due to small number of aircraft in front, the CTA sequence conformance is close to one.
- [2] RTA with arrival manager tool - speed control through RTA function (accuracy standard deviation $\pm 5s$) and data link from arrival manager tool to aircraft. Arrival control horizon time = N minutes to IAF where N can vary from 0 to 90 minutes (same sequence conformance as [1]).

The first case (baseline) represents arrival manager tool operations in Europe with an arrival control horizon time corresponding to typical size of sector in which speed instructions are issued. RTA speed control is not expected to bring significant improvement against speed control issued by the Controllers following arrival manager tool instructions. Therefore both speed controls are considered equal on the short arrival control horizon time.

The second case represents an extension of the arrival control horizon time enabled by RTA equipped aircraft. The arrival control horizon time (90 minutes) is longer but it provides at least the same sequence conformance (80%) as the first case with speed control issued by Controllers.

As a common reference, the above two scenarios are also compared with the basic case with no arrival manager tool, no speed control - the aircraft arrive with their preferred speed and go directly into holding if queuing is necessary (London type of procedure).

The scenarios are described by the following parameters:

Table 2-4: Fuel consumption scenario parameters

Parameter name	Units	Range
Runway capacity – minimum spacing	s	[High – average 81 s]
Cruise Flight Level	FL	350
Speed envelope for Cruise phase	Mach	[0.74 .. 0.78]
Potential Fuel Savings in Cruise phase	kg	4 kg for 15 minutes arrival control horizon time 53kg for 90 minutes arrival control horizon time
Thrust in Descent phase	%	Idle
Speed envelope for Descent phase	CAS/Mach	[250/0.65...290/0.78]
Potential Fuel Savings for entire Descent phase	kg	40
Cost for holding per hour	kg	2,250

Note: for fuel consumption figures refer to Appendix B.

2.5. TRAFFIC

2.5.1. CTA Sequence Conformance

An average traffic spacing of 85s was used based on SESAR performance target values [17] of 80s for arrivals to parallel runway and 94s for arrivals to crossing runway. RTA was assumed to be set to the CTA for equipped aircraft. Different levels of traffic equipage mix are assumed.

2.5.2. Saturation Risk

Two traffic sequences were considered, both with regularly spaced CTAs at 90s apart.

- All aircraft without RTA equipage.
- All aircraft with RTA equipage.

2.5.3. Fuel Economy

Data for 689 aircraft arriving at London Heathrow in a day period from 5 a.m. to 10 p.m. was obtained from EUROCONTROL Central Flow Management Unit (Figure 2-2).

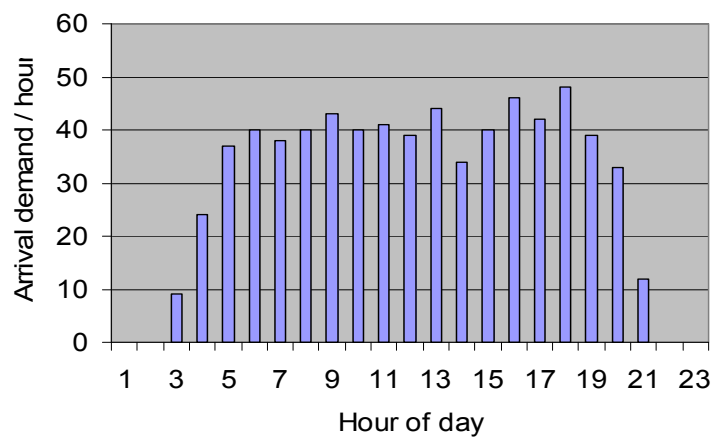


Figure 2-2: Arrival Traffic at Heathrow

2.6. EXPERIMENTAL VARIABLES AND DESIGN

- CTA sequence conformance:

Table 2-5 shows the independent variables used for the CTA sequence conformance experiment. The arrival control horizon time is varied from 0 to 60 minutes before the IAF in ten minute intervals. Sixty minutes corresponds to the average flight time in Europe. The ten minute interval was chosen to give sufficient intermediate points to show any non-linear trends. The proportions of aircraft RTA equipped were chosen by trial and error to show the increased sensitivity of CTA sequence conformance probability for high percentages of aircraft equipped. High traffic density was set to an average spacing of 85s based on requirements from [17].

Table 2-5: Experimental variables for sequence conformance

Independent variable	Range
Arrival control horizon time	{0, 10, 20, 30, 40, 50, 60} minutes
Proportion of aircraft RTA equipped	{0, 50, 80, 95, 100} %
Time keeping accuracy of equipped aircraft (standard deviation)	{5,10}s
Traffic density average spacing	{300(low), 120(medium), 85(high)}s

- Saturation risk:

Table 2-6 shows the independent variables used for the saturation risk experiment. Bunch size variation was derived from fast time simulation referred to in 2.4.2 and proportions of 0 and 100% were chosen for ease of calculation.

Table 2-6: Experimental variables for saturation risk

Independent variable	Range
Bunch size	{2, 3, 4}
Proportion of aircraft RTA equipped	{0, 100}%

- Fuel economy:

Table 2-7 shows the independent variable arrival control horizon time used for the fuel economy experiment. Seventy minutes from IAF was chosen to encompass the average European flight time of an hour. The intermediate values were chosen to give sufficient points to show any non-linear trends.

Table 2-7: Experimental variables for fuel economy

Independent variable	Range
Arrival control horizon time	{15, 25, 50, 70} minutes

Note: A preliminary calculation using BADA accuracy aircraft fuel consumption data was performed for arrival control horizon times of 15 and 90 minutes.

3. CONDUCT OF VALIDATION EXERCISE RUNS

3.1. EXPERIMENT PREPARATION

The probabilistic model and analytical case study were implemented in Microsoft Excel 2002 with analysis toolpack add-in. The BADA web tool was used for aircraft fuel performance. The conduct of experiments was as follows:

- CTA sequence conformance probabilistic model experiment - February to May 2008.
- Saturation risk probabilistic model experiment – October to December 2008.
- Cost benefit analysis - April to May 2008 (BADA model) and in October 2008 (update with more accurate data from Airbus model).

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4. EXPERIMENT RESULTS

4.1. MEASURED EXPERIMENT RESULTS FOR CTA SEQUENCE CONFORMANCE

4.1.1. RTA Accuracy – high ($\sigma = 5s$)

Figure 4-1, Figure 4-2 and Figure 4-3 show the effect of arrival control horizon time on CTA sequence conformance for different levels of equipage and an RTA high accuracy of 5s standard deviation.

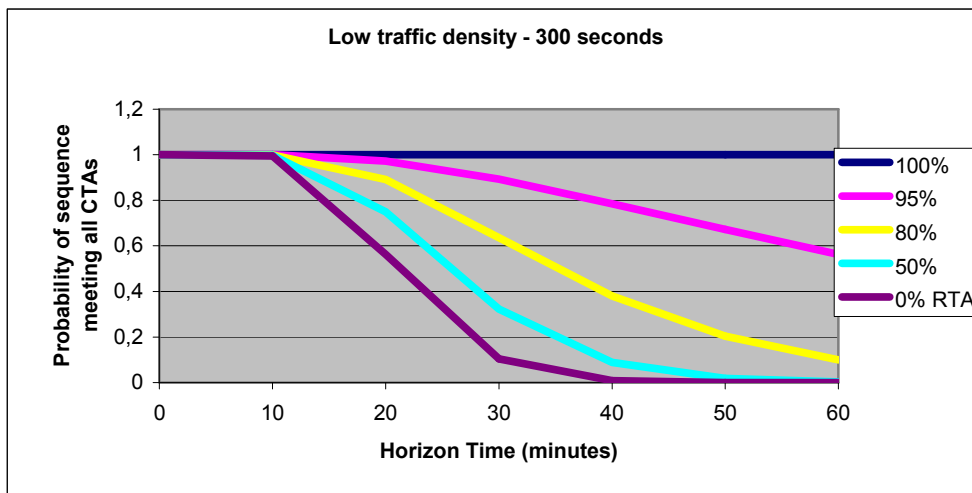


Figure 4-1: CTA sequence conformance in low traffic density

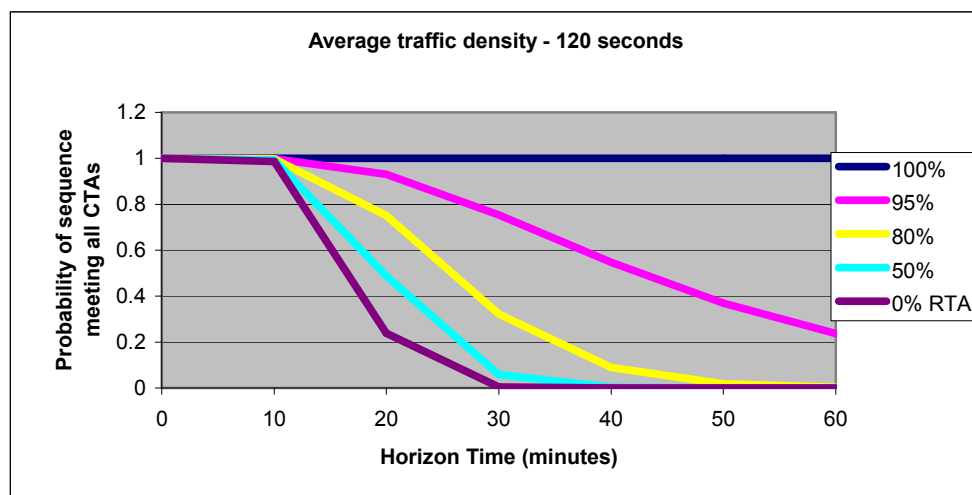


Figure 4-2: CTA sequence conformance in medium traffic density

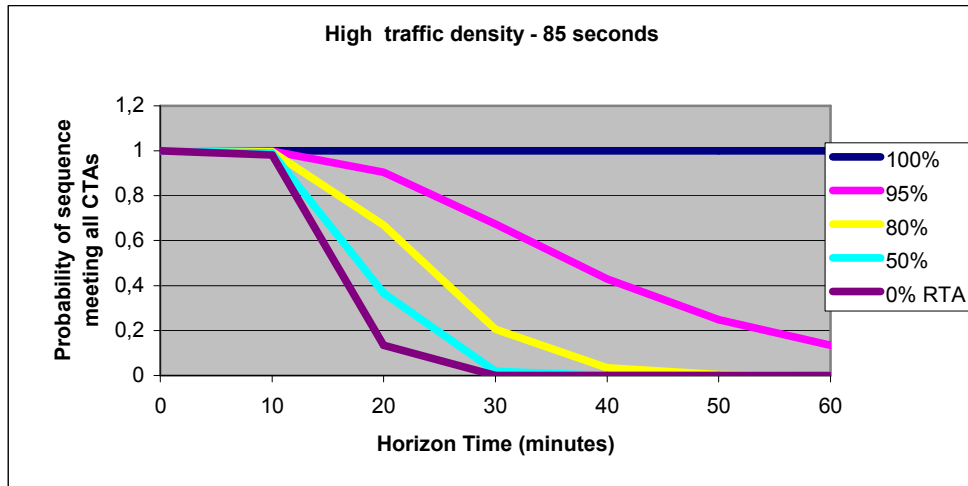


Figure 4-3: CTA sequence conformance in high traffic density

4.1.2. RTA Accuracy – medium ($\sigma = 10s$)

Figure 4-4, Figure 4-5 and Figure 4-6 show the effect of arrival control horizon time on CTA sequence conformance for different levels of equipage and an RTA medium accuracy of 10s standard deviation.

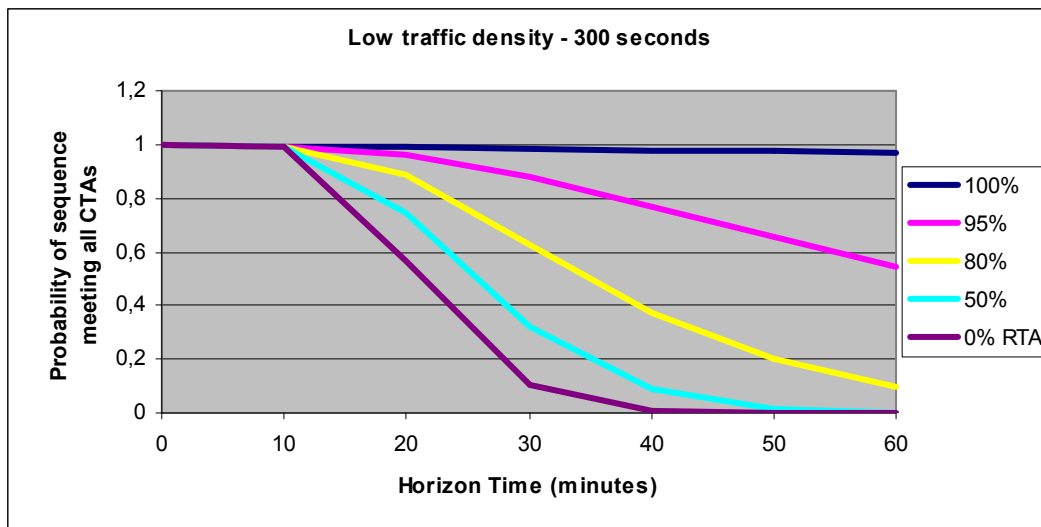


Figure 4-4: CTA sequence conformance in low traffic density

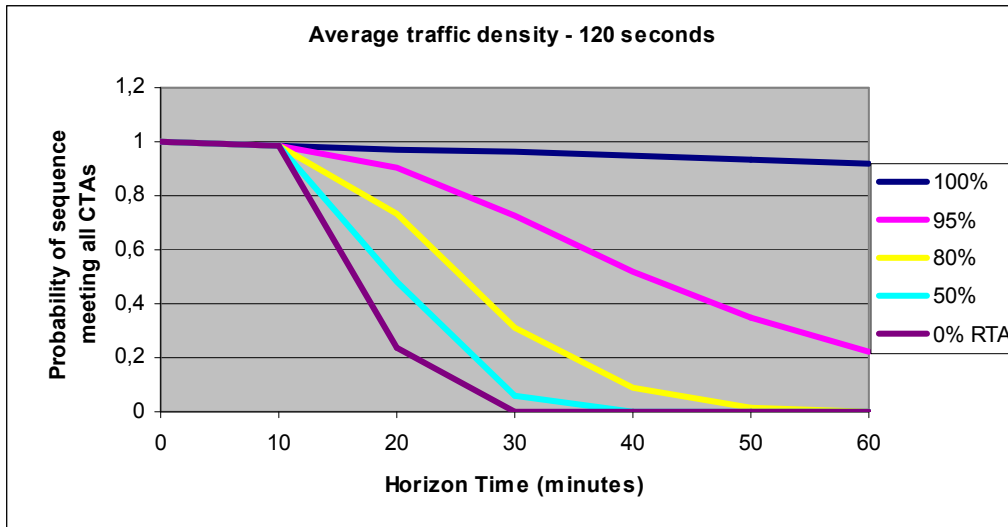


Figure 4-5: CTA sequence conformance in medium traffic density

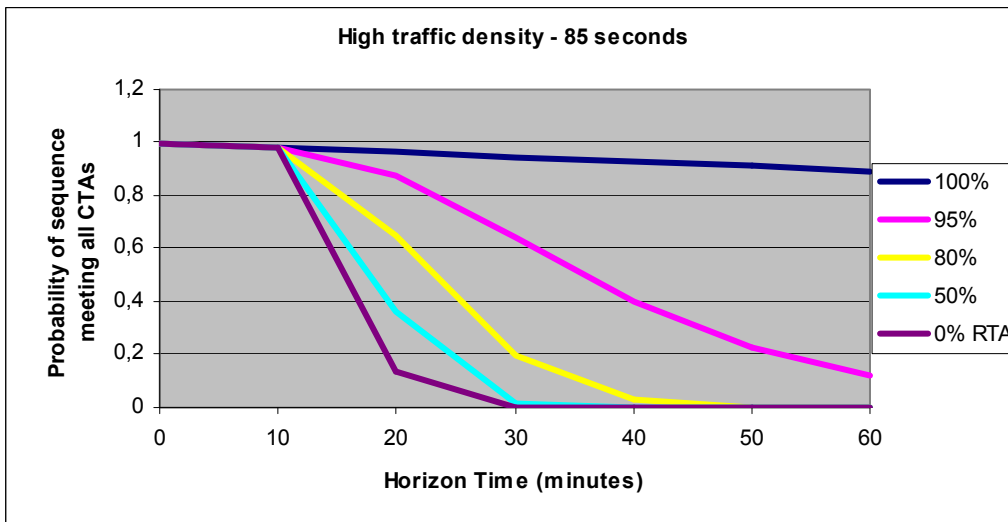


Figure 4-6: CTA sequence conformance in high traffic density

4.2. MEASURED EXPERIMENT RESULTS FOR SATURATION RISK

For a $t_{spacing}$ of 90 s, the table gives the probabilities of bunches of n aircraft occurring in a certain slot of $\pm 45s$ about an aircraft RTA for sequences of RTA equipped and non-equipped aircraft as calculated from equations 7 to 9:

Table 4-1: Probabilities of bunching for RTA equipped and unequipped

	Bunch of 2	Bunch of 3	Bunch of 4
RTA Equipped	6×10^{-6}	10^{-11}	$< 10^{-17}$
Unequipped	0.12	0.004	2×10^{-8}

4.3. MEASURED EXPERIMENT RESULTS FOR EFFECTS ON FUEL CONSUMPTION

4.3.1. Fuel Savings - BADA accuracy

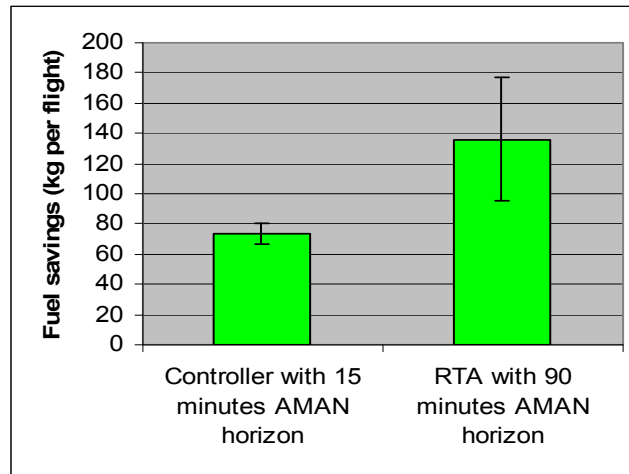


Figure 4-7: Fuel savings (kg) per arrival for arrival control horizon times of 15 and 90 minutes

Figure 4-7 shows average fuel consumption savings relative to a common reference controller without arrival manager. An arrival manager tool reduces the average fuel consumption per arrival by 70 kg for this scenario compared with holding alone. An RTA with arrival manager tool can nearly double these savings (for 100% arrivals RTA equipped). The savings are in the magnitude of one percent of the total fuel burn of an average flight. These results were computed with a basic aircraft model (BADA) described in Annex B.

4.3.2. Fuel savings - Airbus accuracy

Figure 4-8 shows results of updating fuel savings calculation using more accurate fuel consumption data from Airbus (Airbus fuel consumption data cannot be published for confidentiality reasons).

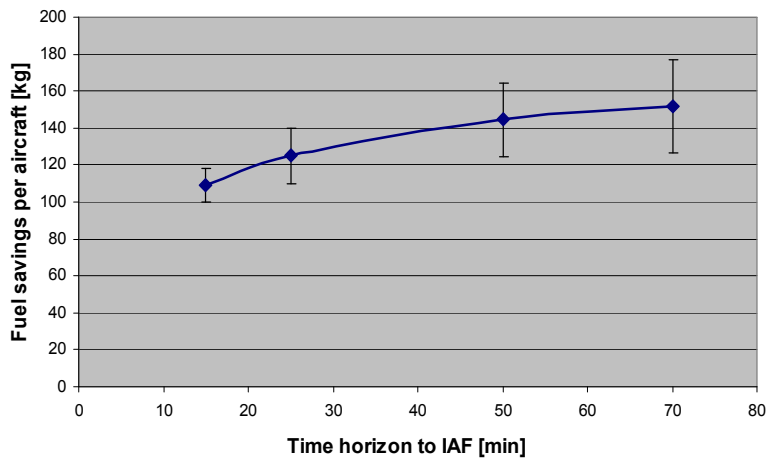


Figure 4-8: Fuel savings as function of arrival control horizon time

4.4. CONFIDENCE IN EXPERIMENT RESULTS

4.4.1. Quality of Results of Experiments

4.4.1.1. CTA Sequence Conformance

The main factors affecting accuracy are:

- i) Arrival time accuracy of equipped aircraft. Two values were tested ($\sigma=5s$ and $\sigma=10s$) as candidates for Airbus specifications for FMS/RTA manufacturers.
- ii) Arrival time accuracy of unequipped aircraft. This figure is based on expert judgement and has an estimated associated error of the order of $\pm 30s$ (standard deviation).

4.4.1.2. Saturation risk

The absolute accuracy of the normal distribution at such tail extremes may be orders of magnitude [20], but the ratios between RTA equipped and unequipped aircraft could still be significant.

4.4.1.3. Effects on Fuel Consumption

The results linked to increase of arrival control horizon time depend on the fuel consumption accuracy (Table 4-2), savings per flight phase and on the traffic characteristics: Traffic type mix, Runway utilization ratio and Variability of TMA entry flow.

Table 4-2: Error analysis of fuel savings

	Accuracy of fuel savings per phase (% of actual total savings)			
Arrival control horizon time	Cruise savings	Descent savings	Paths stretching savings	Total weighted error
15 minutes	$\pm 150\%$ with 2% weighting	$\pm 10\%$ with 27% weighting	$\pm 5\%$ with 71% weighting	$\pm 9\%$
90 minutes	$\pm 150\%$ with 17% weighting	$\pm 10\%$ with 9% weighting	$\pm 5\%$ with 74% weighting	$\pm 30\%$

Fuel consumptions are computed with the BADA model and with corrections from Airbus for Cruise flight with reduced speed. This is done for the A320 only and the figures are applied to all arrivals independent of the real aircraft type. On average this is assumed to be precise enough because the traffic mix results in an average aircraft size similar to the A320. The principle is described in (Appendix A).

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5. ANALYSIS OF EXPERIMENT OUTCOMES

5.1. ANALYSIS OF OUTCOMES ON THE BASIS OF DETERMINED HYPOTHESES

Table 5-1 summarises the outcome and recommendation for each hypothesis.

Table 5-1: Performance hypothesis testing

ID	Hypothesis	Outcome	Recommendation
PC1	Probability CTA sequence met increases with increasing RTA equipage	True for arrival control horizon times greater than 10 minutes. e.g. for 30 minutes arrival control horizon time and average traffic density, probability increases from 0.0 to 1.0 when equipage increases from 0% to 100%	Accept hypothesis for arrival control horizon times greater than 10 minutes
PC2	Probability CTA sequence met reduces gracefully with decreasing RTA accuracy	True e.g. for average traffic density, probability of CTA sequence conformance decreased from 0.95 to 0.92 (3%) for 95% equipage and 20 minutes arrival control horizon time when RTA accuracy decreased from $\pm 5s$ to $\pm 10s$ (reduction of 50%)	Accept hypothesis
PS1	Probability of saturation less with RTA	True – probability of bunch sizes from 2 to 4 are lower with RTA by factors of more than 10^4	Accept hypothesis
EF1	Fuel savings greater for RTA than unequipped aircraft	True e.g. fuel savings $36 \pm 36kg$ (33%) greater for RTA from arrival control horizon time of 60 minutes compared to 15 minutes without RTA	Accept hypothesis with note that estimated error is high

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6. CONCLUSION

Probabilistic modelling is used to investigate the air traffic control performance benefits of aircraft respecting a RTA at an initial approach fix (IAF~10,000 feet) agreed in advance, typically before top of descent. Results indicate the probability of a sequence of controlled times of arrival (CTA) all being met, greatly increases with proportion of aircraft RTA equipped. It follows that RTA equipage enables stable sequences for arrival control horizon times much longer than today with an air traffic controller using an arrival manager tool. Reducing RTA accuracy (standard deviation) from $\pm 5s$ to $\pm 10s$ (50%), reduced CTA sequence conformance (probability) slightly from 0.95 to 0.93 (3%) for average traffic density and 20 minutes arrival control horizon time. The risk of a large busy terminal area saturating due to bunching at the IAF is reduced by orders of magnitude when all aircraft are equipped with RTA.

RTA enabled arrival control horizon times increase fuel savings (relative to a controller without an arrival manager) from $110\pm 10kg$ at 15 minutes to $150\pm 25kg$ at 70 minutes. Approximately 40 kg of fuel saved per arrival equates to about 20 tonnes of fuel (and the related amount of pollution such as 60 tonnes of CO_2) saved per arrival runway a day assuming about 500 arrivals per day. Fuel savings analysis by Airbus related to optimisation of vertical profile, better metering at Initial Approach Fix (IAF) and more accurate Estimated Times of Arrival (ETA) are included in appendices.

Issues relating to the introduction of RTA that could be addressed include (i) sequence stability in the event of an aircraft failing to meet its CTA to the extent of having to insert it elsewhere in the sequence and (ii) separation between aircraft when one or more is performing a RTA.

Within the subset of validation objectives identified for the scope of this study, results are consistent with the idea that controlling aircraft with FMS RTA has performance benefits.

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APPENDIX A - DETAILS OF EFFICIENCY DUE TO MORE OPTIMAL DELAY ABSORPTION CASE STUDY

Analytical case studies using Microsoft Excel were performed with fuel and time figures based on the following assumptions.

A.1 DIFFERENT WAYS FOR ARRIVALS TO ACHIEVE A GIVEN AIRBORNE DELAY

The airborne delay is computed per arrival on the basis of one dedicated arrival runway on which arrival demand frequently exceeds runway capacity. Therefore peaks need to be absorbed through airborne delay. A particular 24 hour period of this kind of traffic is simulated with three different cases:

1. No arrival manager tool, no speed control - the aircraft arrive with their preferred speed and go directly into holding if queuing is necessary (London type of procedure).
2. With arrival manager tool - speed control through Controller via speed instructions. Arrival control horizon time = 15 minutes to IAF. Controllers' speed instructions are assumed to be as efficient as the RTA function.
3. RTA and arrival manager tool - speed control through RTA function. Arrival control horizon time = 90 minutes to IAF (speed instructions by the air traffic controller are not considered feasible for large arrival control horizon times involving several sectors. And the arrival manager tool sequence conformance would be insufficient using Controller speed control instructions. The RTA should be transmitted to the aircraft via data link).

A.2 SIMPLIFYING ASSUMPTIONS

1. Use of BADA aircraft model.
2. For fuel consumption computation all arrivals are treated as A320s for following reasons:
 - Airbus could complement the BADA output with factory data for the A320.
 - In order to avoid the computation for all aircraft types.
 - BADA A320 comes close to an average aircraft size and consumption.
3. Cruise flight level assumed to be FL 350 for all arrivals.
4. The simulation scope goes from cruise down to an IAF assumed to be at FL 100.
5. Descent: always idle descent from FL 350 to FL 100 is assumed (Airbus: Open Descent). The assumption covers different cas/mach pairs and the fuel consumption is taken into account during idle descent according applied speed.
6. Default speed A320: in cruise mach 0.78, in descent mach 0.78, 300 kias.
7. No deviation from ISA.

A.3 WITHOUT ARRIVAL MANAGER TOOL, AIRBORNE DELAY ACHIEVED IN HOLDING

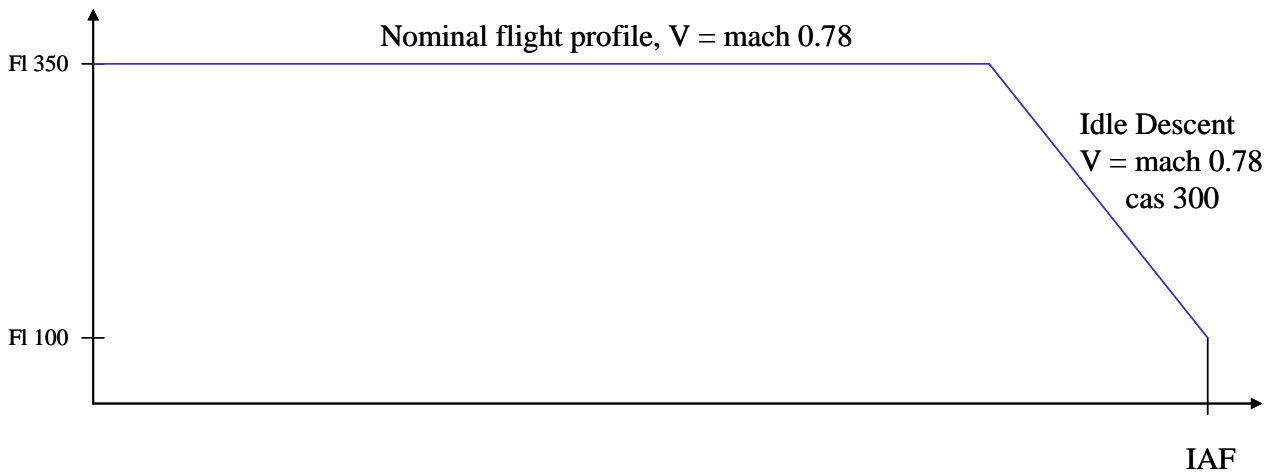


Figure A.1: Nominal (default) profile, Altitude (FL) versus distance

The complete airborne delay is achieved in holding. According BADA A320 model the consumption is 2250 kg/hour holding at FL 100, cas 220.

Fuel consumption is considered as comparison to the nominal flight profile above. If there is no arrival manager tool (no anticipation of arrival delay) then the delta is only the fuel burnt during holding.

A.4 ARRIVAL CONTROL HORIZON TIME = 15 OR 90 MINUTES TO INITIAL APPROACH FIX

Fuel consumption is considered as comparison to the nominal flight profile above in blue (as for the preceding case).

Aircraft maximum speed is limited to $V_{nominal}$ ($V_{max} = V_{nominal}$). Idle Descent is assumed for $V_{nominal}$ and V_{min} . The delay absorption capacity during cruise depends directly on the arrival control horizon time. Remaining delay (after absorption during cruise and descent) delay is absorbed in holding, according BADA A320 model at 2250 kg/hour for FL 100, CAS 220.

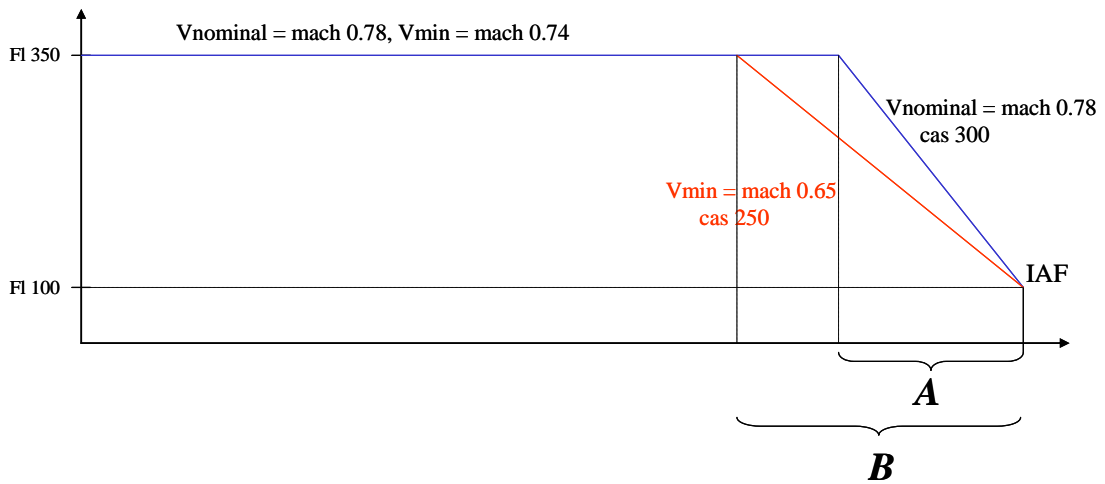


Figure A.2: Minimum speed profile (red), Flight level versus distance

A.4.1 Descent Phase

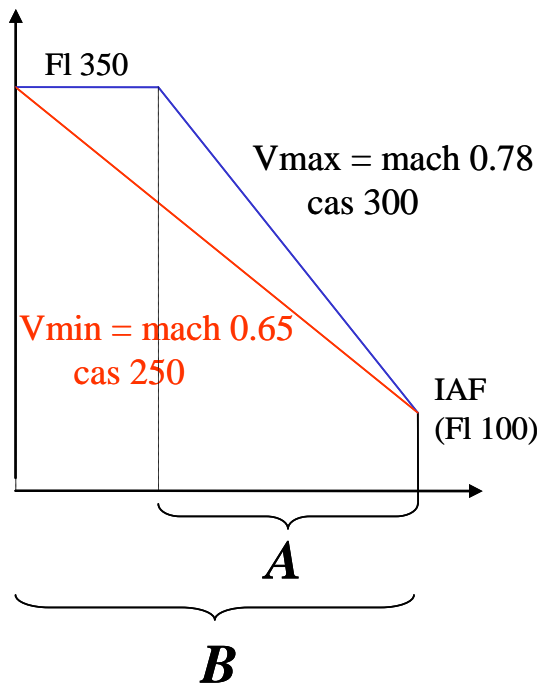


Figure A.3: Descent profile comparison, Flight level versus distance

Aircraft weight = 60 tons at TOD and during horizontal segment.

Table A.1: Flight segment performance data

	Descent A (idle, gradient ~ 4°)	Descent B (idle, gradient ~ 3.2°)	Horizontal Segment At mach 0.78
Length [NM]	61.5	72.0	72.0 – 61.5 = 10.5
Duration [s]	545	762	84 (t = s / v)
Consumption [kg]	59 (BADA)	83 (BADA)	64 (BADA)

From the previous table data follows:

Table A.2: Descent performance comparison A/B

	Duration [s]	Consumption [kg]
Fast Descent = Horizontal segment + Descent A	84+545 = 629	64+59 = 123
Slow Descent = Descent B	762	83

The maximum delta between fast and slow descent (for the same along track distance = 72 NM) is:

- in time: 133 seconds;
- in fuel consumption: 40 kg savings when flying slow.

The maximum absorbable airborne delay during descent is 133 seconds and the corresponding savings are the maximum possible during descent (40 kg).

For delays <133 seconds the savings are interpolated between 0 and 40 kg.

The following are used:

- max delay absorbable in descent = 2.25 minutes;
- corresponding savings = 17.8 kg / minute.

A.4.2 Cruise Phase (Arrival control horizon time = 15 minutes to Initial Approach Fix)

Fuel consumptions have to be compared to the nominal case on a distance to fly basis. The reference distance shall be the nominal case for the 15 minutes arrival control horizon time. Its descent part corresponds to 61.5 NM and 545 seconds. To achieve 15 minutes (900 s) there are 345 s of cruise missing. These correspond at FL 350 and mach 0.78 to 43 miles to fly.

Savings during Cruise phase:

The minimum speed during cruise is assumed to be mach 0.74. This speed allows savings of 166 kg/h (according Airbus) compared to mach 0.78. At minimum speed the 43 NM are flown in 363 seconds. Consumptions in Kg/NM are:

- mach 0.78 (= 449.6 TAS): 2507 kg/h / 449.6 NM/h = 5.58 kg/NM;
- mach 0.74 (= 426.5 TAS): [2507-166 kg/h] / 426.5 NM/h = 5.49 kg/NM.

and in kg for 43 NM cruise to fly:

- mach 0.78: 5.58 kg/NM * 43NM = 239.8 kg;
- mach 0.74: 5.49 kg/NM * 43NM = 236.0 kg.

The following data are used:

- max delay absorbable in cruise = 363s – 345s = 0.25 minutes
- corresponding complete savings = 239.8kg – 236kg = 3.8 kg

A.4.3 Cruise Phase (Arrival control horizon time = 90 minutes to Initial Approach Fix)

Analog to the previous paragraph: The reference distance shall be the nominal case for the 90 minutes arrival control horizon time. Its descent part corresponds to 61.5NM and 545 seconds. To achieve 90 minutes there are 4855 s of cruise missing. These correspond at FL 350 and mach 0.78 to 606 miles to fly.

Savings during Cruise phase:

The minimum speed during cruise is assumed to be mach 0.74. This speed allows savings of 166 kg/h (according Airbus) compared to mach 0.78. Then the 606NM are flown in 5115 seconds. Consumptions in Kg /NM are:

- mach 0.78 (= 449.6 TAS): 2507 kg/h / 449.6 NM/h = 5.58 kg/NM;
- mach 0.74 (= 426.5 TAS): [2507-166 kg/h] / 426.5 NM/h = 5.49 kg/NM.

and in kg for 606 NM cruise to fly:

- mach 0.78: 5.58 kg/NM * 606NM = 3380.8 kg;
- mach 0.74: 5.49 kg/NM * 606NM = 3327.9 kg.

The following data are used:

- max delay absorbable in cruise = $5115s - 4855s = 4.3$ minutes;
- corresponding complete savings = $3380.8 \text{ kg} - 3327.9 \text{ kg} = 53 \text{ kg}$.

A.5 AIRBORNE DELAY ABSORPTION PRIORITIES FOR ARRIVAL MANAGER TOOL AND ANY ARRIVAL CONTROL HORIZON TIME TO INITIAL APPROACH FIX

The fuel savings during descent phase are higher than in cruise phase – probably due to the chosen speed envelope. Therefore airborne delay absorption during descent phase has priority. Remaining delay will be absorbed during cruise phase. If after that there is still delay to be absorbed then holding is applied. In the Excel files, the sum of time to loose in descent and time to loose in cruise:

- 15 minutes arrival control horizon time sum max time to loose = 2.50 minutes;
- 90 minutes arrival control horizon time sum max time to loose = 6.55 minutes.

From an algorithm point of view there is no difference between the different arrival control horizon times as long as the descent phase is entirely covered.

APPENDIX B - BENEFITS FROM OPTIMISATION OF VERTICAL PROFILE WITHIN ATC PUBLISHED CONSTRAINTS (ALT/SPEED) DOWN TO MERGE POINT (AIRBUS)

B.1 PRINCIPLE

In the INITIAL 4D concept, once the CTA is uplinked to the aircraft, the aircraft is flown in FMS full managed modes on the FMS optimised trajectory (altitude and speed profiles in particular). FMS optimisation considers all speed/altitude/time constraints. The resulting trajectory is considered as the most optimised one “within the constraints”. Current ATC ways of managing incoming flows include assignment of tactical vectors to the aircraft, aircraft being requested to maintain certain speed/certain altitude level or certain heading or track. Benefits resulting from reduced lateral path stretching before or at IAF have already been assessed. Use of RTA and FMS full managed mode is also expected to bring benefits in the vertical (speed and altitude) dimension.

Use of FMS full managed modes will reduce occurrence of conservative ATC radar vectoring techniques like:

- early descent initiation: ATC request AIRCRAFT to initiate descent earlier than optimal for the vertical profile, resulting in shallow descent (or intermediate level off);
- request for intermediate level off when not required by ATC published constraints.

From a general point of view, an ATC controller managed “vectored descent” is considered to be (general tendency) less optimised (from a single aircraft flight efficiency point of view) than an “undisturbed” FMS full managed descent. FMS full managed modes coupled with the RTA function offer a systematic optimised alternative while ensuring aircraft sticks to lateral flight plan, within published alt/speed constraints and accurate crossing time at IAF.

B.2 QUANTITATIVE BENEFITS

A quick study allowed to show adverse impact of intermediate level off (refer to Figure B.1 and Table b.1) on fuel consumption for an A320 (GW=66T, no winds).

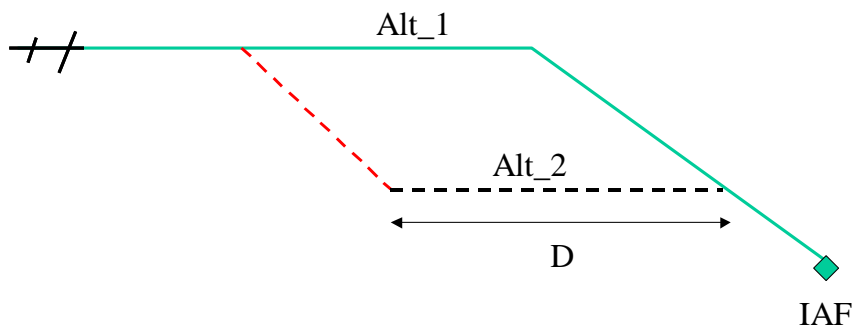


Figure B.1: Intermediate level off influence on fuel consumption: scenario definition

Table B.1: Intermediate level off influence on fuel consumption: K factor

		ALT_1 [FL] / Speed					
		350 / ,78	350 / ,74	FL200 / 300kts	FL200 / 270kts	FL100 / 250kts	FL100 / 220kts
ALT_2 [FL] / Speed	350 / ,78	X	X	X	X	X	X
	350 / ,74	-0,13	X	X	X	X	X
	FL200 / 300kts	1,37	1,5	X	X	X	X
	FL200 / 270kts	1,18	1,31	-0,19	X	X	X
	FL100 / 250kts	2,71	2,84	1,34	1,53	X	X
	FL100 / 220kts	3,09	3,22	1,72	1,91	0,38	X

$$\text{Fuel_consumption_2} - \text{Fuel_consumption_1} = K * D$$

Where K [kg/NM] is given in the table above and D is the distance in [NM]

Example:

Flying an intermediate 20NM level off segment at FL100 /250kts instead of .78 at FL350 corresponds to a fuel increase of 54 kg on an A320.

Figure B.2 shows an extract from ADS-B recordings (source=EUROCONTROL) of south-west incoming traffic flying STAR SABLE to IAF BALOD at Paris Charles-De-Gaulle airport (LFPG). An early descent initiation can be seen resulting in a 35NM long average intermediate level off at FL280. On the chart can also be noted sparse intermediate level offs at various altitudes.

Expected fuel benefits resulting from vertical optimisation offered by FMS are to be considered on a case by case basis since they will significantly depend on the reference scenario (the more penalizing the reference scenario is, the greater the benefits from FMS vertical optimisation).

Results from the AURORA project (carried out 2007-2008 and involving SAS A330 aircraft at Arlanda airport) allowed quantitative fuel benefits resulting from systematic use of FMS managed modes at airline preferred Cost Indexes compared to reference cases where aircraft is radar vectored (speed and altitude). For the A330, results showed fuel benefits of around 100kg due to vertical (speed/altitude) optimisation only. The corresponding figure for an A320 would be around 40 kg.

ARRIVALS STAR SABLE TO IAF BALOD

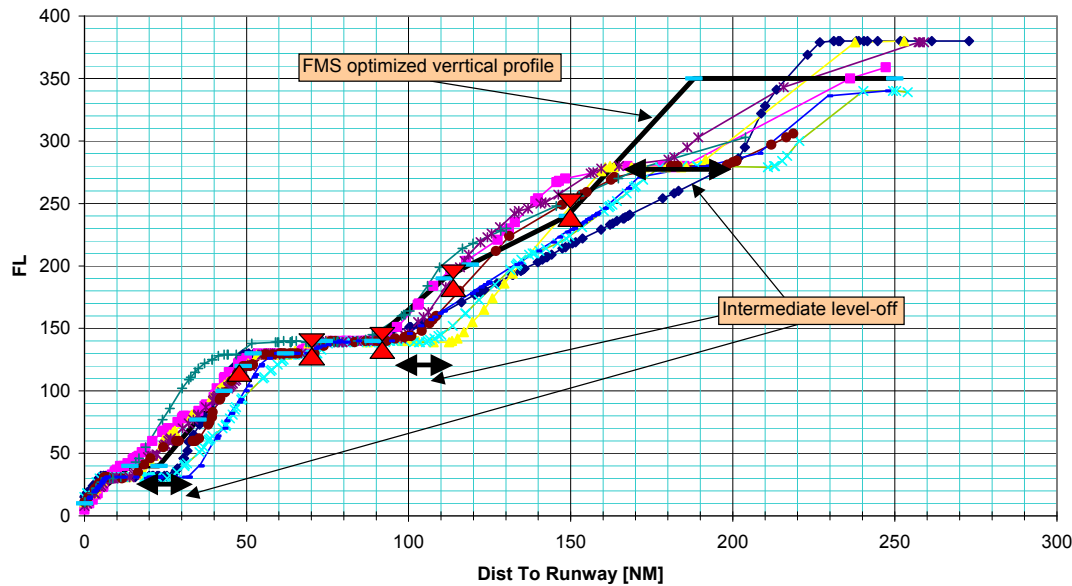


Figure B.2: Extract from ADS-B recordings of south-west incoming traffic at LFPG (STAR SABLE to IAF BALOD) – comparison with FMS optimised trajectory within published constraints

B.3 LIMITATIONS

Fuel benefits resulting from optimisation of vertical profiles via extensive use of AIRCRAFT FMS FULL MANAGED modes is expected to vary with traffic density:

- in low traffic density, there is less need for tactical instructions from ATC to solve conflicts for example. ATC is more likely to be able to clear the aircraft on its preferred and optimised trajectory. This is for example the case today where idle descent clearances are given to aircraft at night or early in the morning (results from AURORA project).
- In high traffic conditions, ATC is more likely to give aircraft short-term tactical clearances (e.g. level-off or heading to solve conflicts). High workload on the ATC controller side may also results in this case in descent clearances not given in time and inducing intermediate level-offs on the aircraft side.

To account for this aspect, fuel benefits related to optimisation of vertical profiles down to merge point via use of INITIAL 4D is to be considered as a function of traffic density. Proposal for potential gains are given in Table B.2.

Table B.2: Fuel Benefits from optimisation of vertical profiles within ATC published constraints as a function of traffic density (A320)

	HIGH DENSITY	LOW DENSITY	INITIAL 4D Enabler
Fuel Benefits (average per aircraft) from optimisation of vertical profile within ATC published constraints	20 kg	40 kg	Downlink of 4D predicted trajectory => AIRCRAFT can be cleared on more optimized trajectory and remains predictable

APPENDIX C - BENEFITS FROM BETTER METERING AT MERGE POINT (AIRBUS)

C.1 PRINCIPLE

RTA functionality is expected to result in more accurate metering at merge point (e.g. IAF) than current ATC vectoring practices. RTA functionality will be able to deliver aircraft at IAF at required time with accuracy up to +/-10sec on a 95% probability basis.

Required metering accuracy at IAF depends on possibility to absorb/lose time between IAF and the runway. This is a characteristic of the airspace considered:

- Some airports for which delay can be absorbed in TMA (e.g. Charles De Gaulle LFPG has a large TMA and allows extensive radar vectoring, in particular path stretching), will not aim at obtaining very accurate aircraft metering at IAF since aircraft crossing time error at IAF can be absorbed in TMA.
- On the contrary, airports for which TMA is small and for which delay can hardly be absorbed in TMA, will aim at metering aircraft at IAF with more accuracy (e.g. Heathrow EGLL which TMA is rather small and shared with 5 other airports uses “stacks” to ensure correct metering at IAF) thus pushing radar vectoring (and ultimately holding) upstream (before IAF).

Note: Paris TMA is around 4 times larger than London TMA.

From a general standpoint, to maintain continuous pressure at the runway and thus maximize capacity, since traffic metering at IAF is not perfect, the arrival manager tool has to compute CTA at merge point (IAF) based on a time to fly along a “standard” route from IAF to runway which is longer than shortest route by a certain margin. This is to ensure early/late traffic at IAF can be handled in TMA via path stretching or direct routing while ensuring continuous 90sec delivery at the runway. The margin to be applied directly depends on metering accuracy at IAF. The greater the metering error at the IAF, the greater the margin applied to maintain capacity. To ensure maximum capacity, required metering accuracy at IAF, required margin to be applied on flight prediction in TMA and airspace design are thus closely linked.

Table C.1: Airspace design parameters

Airspace design	Time flexibility in TMA	Required Metering Accuracy	Required time/dist margin to apply for arrival manager tool predictions
Small TMA	Small	High accuracy	Small
Large TMA	High	Loose	Large

Considering that RTA will result in more accurate metering at IAF, the margin to apply, and thus the duration/length of the “standard” route from IAF to the runway can be expected to decrease. Better metering at IAF is thus expected to result in shorter routes from IAF to runway (on average).

Note: In small TMAs, assuming no flexibility at all on flight duration from IAF to the runway, maximum capacity will be ensured via application of a margin at IAF (arrival manager tool assuming extra time to fly at IAF) to cope with “late” traffic at IAF. This thus results in same mechanism as for the TMA margin. In this case, more accurate metering at the IAF is expected to reduce margin to be applied at IAF.

C.2 QUANTITATIVE BENEFITS

The margin to be considered by the arrival manager tool directly depends on the metering accuracy at the IAF. Estimates for these margins are given in Table C.2.

Table C.2: Required arrival manager tool margin compared to shortest route to maintain capacity as a function of metering accuracy at IAF

Metering Accuracy 95% of time (s)	Required Time margin (s)	Required distance margin at 220 kts (NM)	Equivalent extra fuel burn for A320 at FL100 (kg)
10	20	1.4	12
40	80	5.6	48
60	120	8.4	72

Assuming current ATC vectoring techniques allow to sequence aircraft with an accuracy of +/-1 min, on a 95% basis, introduction of +/-10sec (95% basis) RTA at IAF would result in a trajectory around 7NM shorter on average than current ones. This corresponds to a 60Kg fuel savings on average.

This flight efficiency benefit is expected to be applicable to both:

Large TMAs where radar vectoring allows a certain level of flexibility to compensate eventual metering errors at the IAF: in this case, INITIAL 4D benefits will correspond to “standard” shorter routes from the IAF to the runway.

Small TMAs where adjustment of arrival time at the runway cannot be adjusted in TMA and for which high-accuracy metering is required at the IAF: in this case, INITIAL 4D benefits will correspond to more efficient metering techniques at the IAF: speed adjustment and path stretching/holding at IAF (current technique) replaced by RTA functionality (more efficient), globally reducing flying distance down to or at IAF.

C.3 LIMITATIONS

Benefits resulting from more accurate metering at the merge point are only applicable to high traffic conditions. When traffic demand is low compared to capacity, the need for metering at the IAF is reduced. In this case, traffic can be expedited from IAF to the RWY via direct routing since there is less conflict with other traffic.

Table C.3: Fuel Benefits from better metering at merge point (A320)

	HIGH DENSITY	LOW DENSITY	INITIAL 4D enabler
Fuel Benefits (average per aircraft) from better metering at merge point (from +/-1min to +/-10sec)	60	NONE	Accurate and reliable RTA (+/-10sec, 95% of the time)

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APPENDIX D - BENEFITS FROM REFINED ARRIVAL MANAGER TOOL ESTIMATED TIME OF ARRIVAL DUE TO AIRCRAFT PREDICTED 4D TRAJECTORY (AIRBUS)

D.1 PRINCIPLE

In the current ATM system, ground trajectory predictors (ground TP) are already capable of computing the Estimated Time of Arrival (ETA) of incoming aircraft. This prediction is not very accurate since the ground TP has only access to limited information about the aircraft (mainly aircraft type, position, altitude...); aircraft gross weight or airline cost index (driving optimised speed strategy for the aircraft) are not used since these data are not available. Ground TP predictions are completed by historic data (radar plots) so that the computed ETA is more or less a statistical computation.

The consequences of this process are two-fold:

- the ETA computed by the ground TP is characterized by a large uncertainty that is estimated to be around +/-3min compared to the INITIAL 4D aircraft ETA;
- the CTA as computed by the arrival manager tool being based on ground TP predictions, current computed CTAs do not take into account aircraft preferred ETAs, and thus do not take into account the airline fuel/cost strategy.

Assuming the ground TP is fed with an INITIAL 4D down linked ETA, the arrival manager tool computed CTA is more likely to be closer to the airline preferred ETA and thus to be closer to an optimum trajectory.

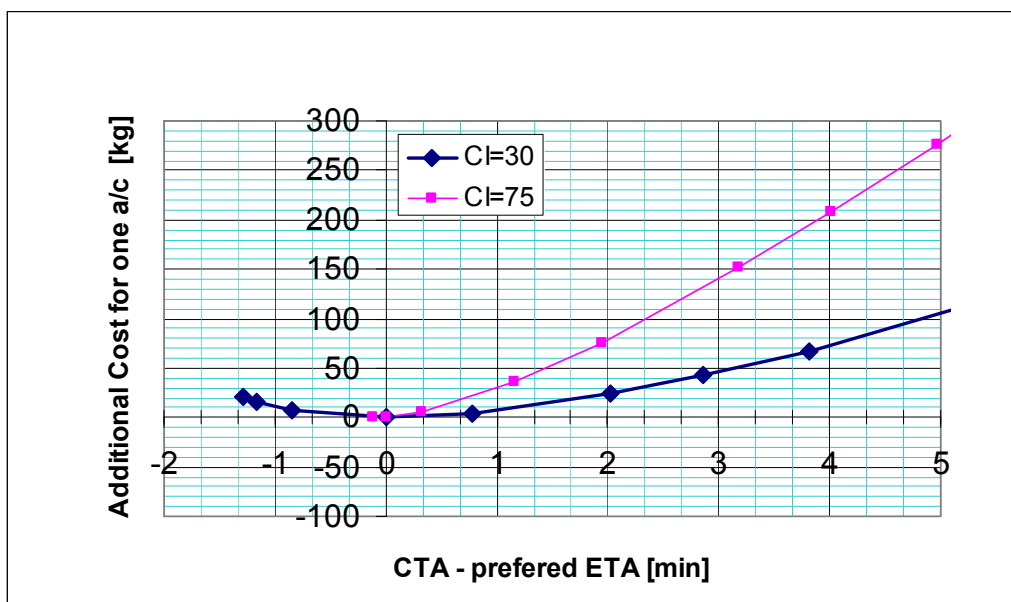


Figure D.1: Additional total cost impact for the airline due to assigning CTA different from airline preferred ETA

Example for one particular case: Consider an A320 for which aircraft preferred ETA based on CI=30 is equal to 00:30:00.

Suppose that the ground TP computes ETA=00:32:00 (prediction error=2min).

Should the arrival manager tool assign CTA = ground_TP_ETA = 00:32:00, this corresponds for the airline to an additional cost of 25 kg compared to ideal case CTA = aircraft_ETA = 00:30:00.

D.2 QUANTITATIVE BENEFITS

Considering ground_TP uncertainty was characterised by uniform error distribution +/-3min, it has been shown that, on average, use of INITIAL 4D aircraft downlinked ETA in place of ground_TP computed ETA for CTA computation, results in an average total cost benefit equivalent to 10kg.

D.3 LIMITATIONS

These benefits resulting in use of INITIAL 4D aircraft downlinked ETA in place of ground TP ETA are applicable only when CTA are used, that is in high traffic conditions. When traffic density is low, it is expected that use of CTA will be limited or with significantly loose required accuracy.

To allow for this aspect, benefits from use of aircraft downlinked ETA are to be considered as a function of traffic density.

Table D.1: Fuel Benefits from use of aircraft downlinked/preferred ETA (A320)

	HIGH DENSITY	LOW DENSITY	INITIAL 4D enabler
Total Cost Benefits (average per aircraft) from use of aircraft downlinked/preferred ETA.	10 kg	NONE	Downlink of aircraft preferred ETA.