Aircraft Punctuality at Arrival Terminal-Area: Impact on Sequence Conformance, Saturation and Cost

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Aircraft arrival punctuality is a key performance measure of the Single European Sky Air Traffic Management Research (SESAR) target concept. A large source of uncertainty in landing times today is due to the merging of poorly synchronised traffic streams in the terminal area (TMA). The objective of this collaborative study was to evaluate benefits of aircraft accurately controlling their own entry time in to the arrival terminal area. Probabilistic modelling is used to investigate the air traffic control performance benefits of aircraft respecting a Controlled Time of Arrival (CTA) at an initial approach fix (IAF~10,000 feet) agreed up to about one hour before with an accuracy of ±10s, 95% of the time. Results indicate the probability of a sequence of CTAs all being met within a tolerance of ±30s, greatly increases with proportion of aircraft RTA equipped. RTA equipage enables CTA sequences to be met for arrival control horizon times much longer than today with an air traffic controller using an arrival manager. The risk of a busy TMA saturating or having to re-sequence due to bunching at the IAF is reduced by orders of magnitude when all aircraft are equipped with RTA. 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±10kg at 15 minutes to 150±25kg at 70 minutes.

Nomenclature

<table>
<thead>
<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
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<tr>
<td>CTA</td>
<td>Controlled Time of Arrival</td>
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<td>FMS</td>
<td>Flight Management System</td>
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<td>IAF</td>
<td>Initial Approach Fix</td>
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<td>RTA</td>
<td>Required Time of Arrival</td>
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<td>SESAR</td>
<td>Single European Sky ATM Research</td>
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<tr>
<td>TMA</td>
<td>Terminal Area</td>
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I. Introduction

STUDIES on designing a more structured terminal area (TMA) for merging traffic streams together, highlighted the importance of protecting the TMA from poorly synchronized streams of arrival traffic. The degree to which traffic streams are synchronized greatly determines the efficiency of the merging process. The lower the synchronization 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. 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.

Entries to TMAs typically vary between 10,000 and 25,000 feet so that synchronised TMA entry times agreed during cruise 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 and relative 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.
Many aircraft are equipped with flight management systems that offer the ability to arrive at a requested time. 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\textsuperscript{11}. 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 (EEC) and Airbus was to evaluate benefits of aircraft accurately controlling their own entry time in to the arrival terminal area. An accuracy of ±10s, 95% of the time, was assumed, based on a state of the art review\textsuperscript{11}. Probabilistic models of aircraft arriving at several IAFs trying to respect a sequence of CTAs within ±30s\textsuperscript{3} 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 reference 2 a simple calculation for potential fuel benefits of using speed control instead of path stretching is suggested and in reference 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.

Chapter II describes the air traffic control concept of synchronising controlled times of arrival, aircraft time keeping and the experiment hypotheses. Models of sequence conformance, saturation risk and fuel economy are defined in chapter III. Chapter IV describes the scenarios, traffic and metrics used. Results for the three model based experiments are presented in graphical and tabular form along with discussion in Chapter V. Conclusions for the three experiments are given in chapter VI.

II. Theory

A. Arrival Traffic Control

The operational scenario assumed for this study is compatible with the main principles of 4D trajectory management outlined in SESAR target operational concept\textsuperscript{7}. Aircraft agree to meet a CTA at the entry to a terminal area defined by an initial approach fix typically at about 10,000 feet. For a large TMA like Paris, the IAF may be between 15 to 25 minutes from landing on the runway.

CTAs are determined by ATC typically using an arrival manager tool. Such calculations might take into account down-linked aircraft Expected Times of Arrival (ETA)\textsuperscript{s} as well as traffic flow, and weather conditions (possibly also aircraft RNAV capabilities). Furthermore CTAs may be calculated to enable continuous descents. CTA constraints would be up-linked to suitably equipped aircraft as a RTA and then the aircraft Flight Management System (FMS) function would be expected to fly the aircraft so as to meet the RTA constraint\textsuperscript{7}.

B. Aircraft Time Keeping Capability

For the study, the aircraft FMS RTA functionality was assumed to be characterized by the capability to comply with uplinked absolute CTA within +/-10sec, 95% of the time. The associated 95% reliability is assumed to take into account robustness to weather uncertainty equivalent to about 10 knots average wind speed error.

Before the CTA is uplinked to the aircraft, the aircraft has the option to downlink to ATC its:

- preferred ETA at IAF (that corresponds to airline preferred cost index i.e. optimal time/fuel strategy)
- earliest arrival time (ETAmi) that corresponds to the aircraft flying at its highest achievable speed.
- latest arrival time (ETAmx) that corresponds to the aircraft flying at its lowest achievable speed.

Note that having the airborne side computing these values results in accurate data since they would take into account aircraft gross weight, aircraft performance data and FMS defined weather parameters.

An [ETAmi, ETAmx] window is assumed to be valuable information for ATC controller and/or arrival manager tool since they will significantly help in computing pertinent CTA to uplink. Having this information available on the ground side would reduce occurrence of aircraft equipage having to refuse absolute CTA (and thus make CTA negotiation harder i.e. more than one iteration) while maximizing cost benefits linked with CTA since they will avoid assignment of conservative CTA which would reduce to some extent corresponding benefits.

Once the CTA is uplinked to the aircraft, the flight crew is able to insert it as RTA into aircraft FMS. The FMS then computes optimum profile to fly down to the RTA point i.e. the IAF, that satisfies the time constraint. As the aircraft flies its planned trajectory, actual flown atmosphere wind/temperature profile may differ from FMS defined weather parameters, thus resulting in the aircraft flying faster or slower than predicted and thus impacting the ETA for the RTA point.
To maintain the aircraft ‘on-time’ at the RTA point, when the FMS predicts that the aircraft will be late or early at the RTA point, it automatically adjusts speed to allow proper conformance to the time constraint.

Figure 1: ETA profile and envelope for an A330 flying a RTA

Figure 2: Descent calibrated airspeed (CAS) profiles: predicted vs flown.

Airbus has developed a fast time simulator called ‘4D-Predictor’ that allows the computation of the trajectory flown by an Airbus aircraft flying a RTA in descent taking into account errors due to weather prediction. An example of such a trajectory for a constant unpredicted 15kts wind error during descent is shown in Figure 1 and Figure 2 in the case RTA is defined at IAF (altitude=5000ft – speed limit=FL100/250kts). RTA is inserted when the aircraft is in cruise at FL370, 200NM from the RTA point. For this study, when the RTA value is defined within [ETAmin, ETAmax] interval, the probability the RTA is satisfied within +/-CTA tolerance is given by equations (2) and (3).

C. Hypotheses

1. Sequence Conformance
   Sequence conformance is the degree to which a sequence of aircraft meets all corresponding individual CTAs. It is expected to increase with RTA equipage. For the purposes of quantitative measurement, sequence conformance is assumed to be the probability of all aircraft in a sequence each meeting their individual CTA. Therefore the corresponding hypothesis under test is:
   • CTA sequence conformance increases with increasing proportion of aircraft equipped with RTA.

2. Saturation Risk
   Saturation risk is related to the probability that so many aircraft arrive in a short space of time that the TMA cannot safely handle anymore aircraft. It is expected that RTA equipped aircraft will be less likely to arrive closer
together than the allowed tolerance i.e. in bunches, than unequipped aircraft due to the more accurate tracking of time. Therefore the corresponding hypothesis under test is:

- Probability of bunching decreases with increasing proportion of aircraft equipped with RTA.

3. Fuel economy

It is expected that extended arrival control horizon times allow delay to be absorbed more efficiently by speed control at high altitude instead of path-stretching at lower altitudes. Therefore the corresponding hypothesis under test is:

- Fuel economy is greater for extended arrival control horizon times enabled by RTA equipage

III. Apparatus

A. Sequence Conformance Model

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).

\[
P_s = \prod_{i=1}^{m} P_u(i) \prod_{j=m+1}^{n} P_e(j) \tag{1}
\]

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 ±CTAT are modelled by normal distributions (2) (see equations 2 and 3).

\[
P = \int_{-\text{CTAT}}^{\text{CTAT}} N(x)dx \tag{2}
\]

\[
N(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2 \right) \tag{3}
\]
Where the mean $\mu$ and standard deviation $\sigma$ take values of $\mu_u$ and $\sigma_u$ for unequipped aircraft and $\mu_e$ and $\sigma_e$ for equipped aircraft. The mean 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 $\sigma_u$. The maximum $\sigma_u$ 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 $\sigma_e$ is assumed to be a constant 5s for any arrival control horizon time.

B. Saturation Risk Model

The following model uses traffic flow theory 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:

$$n(t) = n(t_0) + \int_{t_0}^{t} (f_{in}(t) - f_{out}(t))dt$$  \hspace{1cm} (4)

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

$$t_{minSaturation} = \frac{n_{saturation} - n_{no\,min\,al}}{f_{inMax} - f_{outMax}}$$  \hspace{1cm} (5)

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

$$k_{saturation} = f_{inMax} t_{minSaturation}$$  \hspace{1cm} (6)

A measure for protecting TMA from overload is to ensure the probability $P_{s_{Saturation}}$ 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 CTA tolerance CTAT.

$$P_{bunch2} = 2 \int_{-CTAT}^{CTAT} \int_{Spacing-CTAT}^{Spacing+CTAT} N(x)dx N(y)dy$$  \hspace{1cm} (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.

C. Fuel Economy Model

1. Model inputs:
   - Aircraft performance data (source=Airbus) with initial/preferred Cost Index
   - Required spacing at IAF [s]
   - Log file of typical arrival flow with aircraft initial ETA at arrival control horizon time.
2. **Model outputs:**
   - Average path stretching time at IAF
   - Fuel savings due to reduced path-stretching time through speed adjustment.

3. **Two main scenarios are considered:**
   - **Without arrival manager – delay absorbed by path stretching at IAF**
     
     Incoming flights arrive at IAF at their preferred cost index. Incoming traffic are stacked at IAF and requested to hold by ATC. Aircraft are then cleared to proceed to approach on a first come/first served basis. Aircraft delay is absorbed at IAF by path stretching (ultimately holding) only. With no other constraints, this scenario corresponds to the worst case scenario.
   
     **With arrival manager**
     
     When incoming flights arrive at arrival control horizon time flying at its preferred cost index, the flight is taken into account by the arrival manager in the arrival sequence. The arrival manager computes a CTA which is then uplinked to the equipped aircraft and inserted as a RTA in the FMS.
     
     If the delay cannot be absorbed by speed adjustment alone, the aircraft is vectored or requested to hold at the IAF where remaining delay is absorbed. The aircraft is then cleared to proceed to approach.
     
     This scenario is more optimised than the case where there is no arrival manager since a non negligible part of the delay is absorbed by speed adjustment which is far more optimised from a fuel point of view than absorbing delay by path stretching at IAF.

4. **Aircraft type used for simulation**
   - Airbus A320; Gross Weight = 66 tonnes; Cruise Flight level = 350; Airline preferred Cost Index = $C_{\text{Ref}} = 30$
   - International Standard Atmosphere with no winds

5. **Total cost computation:**
   
   The total cost for all aircraft is the sum of cost for all aircraft due to time $Cost_{\text{Time}}$ and cost for all aircraft due to fuel consumed $Cost_{\text{Fuel}}$.
   
   - **Without arrival manager**
     
     $Cost_{\text{Time}} = C_{\text{Ref}} \sum_{i=1}^{n} \left( ETA(i) + Delay(i) \right)$  

     $Cost_{\text{Fuel}} = \sum_{i=1}^{n} \left( Fuel(ETA(i)) + Delay(i) * FF \right)$

     Where:
     
     $Fuel(ETA(i))$ is the aircraft fuel consumption flying the descent profile down to IAF at its preferred cost index.
     
     $FF$ is the typical aircraft fuel flow when flying 220 knots constant CAS in level flight at FL100.
     
     $Delay(i)$ is the required delay to be absorbed by path stretching at the IAF (Delay = CTA-ETA).
   
   - **With arrival manager**
     
     $Cost_{\text{Time}} = C_{\text{Ref}} \sum_{i=1}^{n} CTA(i)$

     $Cost_{\text{Fuel}} = \sum_{i=1}^{n} \left( Fuel\left[CTA(i); ETA_{\text{Max}}(i)\right] + Remaining \_ Delay \_ Delay * FF \right)$
Where:
\[ \text{Fuel}[\text{CTA}(i), \text{ETAMax}(i)] \] is the fuel consumption of aircraft flying the descent profile with adjusted speed profile to satisfy the CTA. Note that in case CTA is higher than ETAMax(i) (more time has to be absorbed than the aircraft possibly can), all the delay may not be absorbed by speed adjustment only. In this case, the remaining delay is assumed to be absorbed by path stretching at IAF.

FF is the typical fuel flow of flying 220kts constant CAS in level flight at FL100.

Remaining _Delay is the delay that cannot be absorbed by speed adjustments only and is effectively absorbed by path stretching at IAF.

In both cases, with or without arrival manager, the delay is the same (scenario differing only because delay is not absorbed in the same way). Total cost benefits are computed between each scenario as the resulting total cost difference. And, since delay is the same between all scenarios, Total cost benefits due to extended arrival control horizon time are only due to differences in fuel consumption.

### IV. Method

#### A. Scenarios

1. **Sequence Conformance**

   The scenario considered is aircraft arriving at one or several IAF(s) in preparation for landing in sequence on a single runway, where the IAF typically marks the entrance to the TMA at say FL100. The probabilistic model characteristics are given in Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Maximum uncertainty in arrival time of unequipped aircraft (standard deviation)</td>
<td>±30 s</td>
</tr>
<tr>
<td>Uncertainty in arrival time of RTA equipped aircraft (standard deviation)</td>
<td>±5s</td>
</tr>
<tr>
<td>CTA tolerance (standard deviation)</td>
<td>±30 s</td>
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</table>

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

2. **Saturation Risk**

   In the Point Merge project at the EEC\(^1\), real and fast time simulations of a medium sized TMA with four IAFs feeding a dedicated arrivals runway were performed for three different arrival traffic merging techniques. The minimum spacing was 90s and typical values for parameters defined in IIIB were \(n_{\text{saturation}} = 18\), \(n_{\text{nominal}} = 15\), \(f_{\text{inmax}} = 4\) aircraft in 90s and \(f_{\text{onmax}} = 1\) aircraft in 90s. Using equation 5 and 6, a typical value for \(t_{\text{MINsaturation}} = 90s\) and \(k_{\text{saturation}} = 4\). For simplicity of calculation, a CTA tolerance of half the average spacing is assumed ±45s, \(\sigma_u\) is 30s and \(\sigma_e\) is 10s.

3. **Fuel Economy**

   Two scenarios are considered: with arrival manager tool and without. Arrival control horizon times of \{15, 25, 40, 50, 70\} minutes are used. A simplified arrival manager is simulated assigning a CTA (to ensure Heathrow average spacing of 82s) based on estimated ETA. The IAF is located at FL100.

#### B. Traffic

1. **Sequence Conformance**

   A traffic average spacing of 85s was used based on SESAR performance target values\(^3\) of 80s for arrivals to parallel runway and 94s for arrivals to crossing runway\(^3\). RTA was assumed to be set to the CTA for equipped aircraft. Different levels of traffic equipage mix assumed.

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
3. Fuel Economy

Data for 689 aircraft arriving at London Heathrow in a day period (July 2006) from 5 a.m. to 10 p.m. was obtained from EUROCONTROL Central Flow Management Unit.

![Figure 4: Arrival Traffic at Heathrow](image)

C. Metrics
The following metrics are used:

<table>
<thead>
<tr>
<th>Table 2: Metrics for sequence conformance</th>
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<tr>
<td><strong>Metric</strong></td>
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<tr>
<td>Dependent variable</td>
</tr>
<tr>
<td>Probability CTA sequence conformance</td>
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<tr>
<td><strong>Independent variables</strong></td>
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<tr>
<td>Arrival control horizon time</td>
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<tr>
<td>Proportion of aircraft RTA equipped</td>
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<thead>
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<th>Table 3: Metrics for saturation risk</th>
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<tr>
<td><strong>Metric</strong></td>
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<tr>
<td>Dependent variable</td>
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<tr>
<td>Probability of bunch</td>
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<tr>
<td><strong>Independent variables</strong></td>
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<tr>
<td>Bunch size</td>
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<td>Proportion of aircraft RTA equipped</td>
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<tr>
<th>Table 4: Metrics for fuel economy</th>
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<tr>
<td><strong>Metric</strong></td>
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<tr>
<td>Dependent variable</td>
</tr>
<tr>
<td>Fuel savings per aircraft arrival</td>
</tr>
<tr>
<td><strong>Independent variables</strong></td>
</tr>
<tr>
<td>Arrival control horizon time</td>
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</tbody>
</table>

V. Results and Discussion

A. Sequence Conformance

Figure 5 shows how sequence conformance decreases with arrival control horizon time and proportion of aircraft RTA equipped. Hypothesis (1) is true for arrival control horizon times greater than 10 minutes, e.g. for 30 minutes arrival control horizon time, probability increases from 0.0 to 1.0 when equipage increases from 0% to 100%.
Figure 5: Sequence conformance vs arrival control horizon time and proportion of aircraft RTA equipped

B. Saturation Risk
Table 5 shows how probability of bunching decreases with bunch size and RTA equipage. Hypothesis (2) is true – the probability of bunch sizes from 2 to 4 are lower with RTA by factors of $10^4$ or more. The inaccuracy of the normal distribution at such tail extremes may be orders of magnitude\(^2\), but the relative ratios between RTA equipped aircraft and unequipped aircraft could still be significant.

Table 5: Probability of bunching in a CTA tolerance equal to aircraft spacing

<table>
<thead>
<tr>
<th>Bunch of 2</th>
<th>Bunch of 3</th>
<th>Bunch of 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTA Equipped</td>
<td>$6 \times 10^{-6}$</td>
<td>$9 \times 10^{-12}$</td>
</tr>
<tr>
<td>Unequipped</td>
<td>0.12</td>
<td>0.004</td>
</tr>
</tbody>
</table>

C. Fuel Economy
Figure 6 shows how fuel economy with an arrival manager (relative to without) increases with arrival control horizon time.

Because of sequence conformance results, arrival control horizon times greater than 15 minutes are only beneficial for RTA equipped aircraft. Hypothesis (3) is true, fuel savings increase from 110±10kg at 15 minutes arrival control horizon time to 150±25kg at 70 minutes. This figure does not take into account the fuel savings due to a more optimal vertical profile. Additional fuel savings are also expected due to better estimated time of arrival and traffic metering.
VI. Conclusions

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 up to one hour before. 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. 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±10kg at 15 minutes to 150±25kg at 70 minutes.

Approximately 40kg of fuel saved per arrival equates to about 20 tonnes of fuel (and the related amount of pollution such as 60 tonnes of CO2) saved per arrival runway a day assuming about 500 arrivals per day.

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.

Acknowledgments

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References

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