4D trajectories - assessing the cost of time
Cook, A.J.

Presented at NAV09 - Air: Aviation’s Future Trajectories (Organised by the Royal Institute of Navigation), Imperial College, London, 25th November 2009.

The WestminsterResearch online digital archive at the University of Westminster aims to make the research output of the University available to a wider audience. Copyright and Moral Rights remain with the authors and/or copyright owners.

Whilst further distribution of specific materials from within this archive is forbidden, you may freely distribute the URL of WestminsterResearch: (http://westminsterresearch.wmin.ac.uk/).

In case of abuse or copyright appearing without permission e-mail repository@westminster.ac.uk
4D trajectories
- assessing the cost of time

Dr Andrew Cook
Principal Research Fellow
University of Westminster
4D trajectories - assessing the cost of time

- SESAR – 4D trajectories at core of new concept
- European delay – context and method
- Quantifying the cost of time (delay) to an airline
- Airline delay cost management
  - technical challenges for 4D
- The flow management context
  - SESAR revisited (KPAs)
- Opportunities ahead for time/delay management
SESAR – 4D trajectories at core of new concept

Single European Sky ATM Research
- modernisation programme for European ATM
The Business (4D) Trajectory

- Negotiated ‘contract’ with time constraints (hence 4D)
- Shared Business Trajectory (SBT)
  Firstly, a trajectory is negotiated which represents the business intentions of the airline and takes account of Air Navigation Service Provider, ATFM and airport constraints
- Reference Business Trajectory (RBT)
  Negotiation complete: trajectory which airline agrees to fly and ANSP + airport agree to provide; c.f. current practice, from both providers and users, of pre-tactical and tactical changes: new concept designed to minimise changes to trajectories & achieve ‘best business outcome’ for all users
- A key business outcome is reduction of delay
- Matures through ‘Service Levels’ delivered …
The six Service Levels (0-5)

Operation
Implementation
R&D

Source: European ATM Master Plan (2009) (approximately to scale)
The six Service Levels (0-5)

The Royal Institute of Navigation – Aviation’s Future Trajectories
The six Service Levels (0-5)

5
- real-time shapes & volumes

4
- free routeing TMA-TMA

3
- full 4D; multiple CTOs
- Controlled Time of Overfly

2
- initial 4D; uplink/downlink; CTA
- Controlled Time of Arrival

1
- preparing 4D; more RNAV routes
- set by ATC / ATM

0
- best practice roll-out

2009  2013  2017  2020  2025

The Royal Institute of Navigation – Aviation’s Future Trajectories
## The six Service Levels (0-5)

<table>
<thead>
<tr>
<th>Service level</th>
<th>Business (4D) Trajectories</th>
<th>Key features</th>
<th>TMAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>better cross-border operations facilitated through CDM with neighbours; flexible sectorisation management</td>
<td>controller tools for: trajectory management over several sectors (i.e. MSP), near-time deconfliction and trajectory conformance monitoring</td>
<td>more RNAV routes, better capacity due to: more flexibility, reduced separation &amp; tailored arrival procedures, A-CDAs in higher traffic</td>
</tr>
<tr>
<td>1</td>
<td>better optimised trajectories (some times/ airspace); pilot-controller coordinated, optimised en-route cruise-climb</td>
<td>A-RNP for reduced spacing between routes, where required; tactical parallel offsets (instead of vectoring)</td>
<td>A-RNP 1 SIDs and STARs</td>
</tr>
<tr>
<td>2</td>
<td>deployment of BTs &amp; CTA; uplink of ATC constraints &amp; downlink of 4D data; more free routeing in Upper Airspace</td>
<td>free routeing to apply from ToC to ToD, pre-defined routes only where necessary</td>
<td>dynamic adjustment of TMA boundaries according to traffic patterns and runway usage</td>
</tr>
<tr>
<td>3</td>
<td>RBT multiple CTOs &amp; revisions through air-ground data exchange; upstream, small ground-based speed adjustments</td>
<td>two airspace categories - managed &amp; unmanaged</td>
<td>free routeing from TMA exit to entry (except high complexity airspace)</td>
</tr>
<tr>
<td>4</td>
<td>widely shared aircraft position &amp; intent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>dynamic sectors: shapes and volumes adapted in real-time; air-to-air data exchanges</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Navigation News**

The Royal Institute of Navigation – Aviation’s Future Trajectories
European delay – context and method
European delay – context and method

- 21% of arrivals >15 mins late in 2008 (slightly better than 2007)
  - traffic ‘growth’ negative from September 2008 onwards
  - 0.4% in 2008 (c.f. 5% in 2007; forecast -3% for 2009)
- ATFM delays alone in 2008 cost airlines around €1.5 billion
- Many airlines have significant barriers to identifying & quantifying delay costs, even before managing them
- General lack of tools for delay cost management

- 12 aircraft supported across the models
- Costs by phase of flight and by three consistent scenarios
- Shift (KPA) focus from minutes of delay to cost of delay
Quantifying the cost of time (delay) to an airline
Delay cost model & magnitudes

§ Airport charges and handling fees
  – e.g. hit or miss peak charge; penalty from an agent

§ Maintenance
  – extra minutes of wear & tear on airframe & powerplants
  – gate-to-gate (workload) model for marginal costs
  – line/transit + A, C & D checks (- overheads) converted to hours basis

§ Crew
  – derive marginal from unit costs; wide cross-section AO schemes
  – block/flight duty hours regNs, sectors flown and overnight stopovers
  – could be zero (‘sector pay’); c.f. overtime with a high cost base

§ Fuel and emissions (EU ETS: extending to aviation from 01 JAN 12)
  – fuel burn from Lido OC; CO₂/tonne: €0.03 - €30 (€13 - Nov 09)

§ Passenger costs: AO ‘hard’ + AO ‘soft’ (+ ‘internalised’) ...
Passenger costs of delay to the airline

The Royal Institute of Navigation – Aviation’s Future Trajectories
Passenger costs of delay to the airline

The Royal Institute of Navigation – Aviation’s Future Trajectories

Soft cost model included Kano satisfaction modelling
## Passenger costs of delay to the airline

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>1-15 mins</th>
<th>16-30 mins</th>
<th>31-45 mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>B737-300</td>
<td>12</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>B737-400</td>
<td>14</td>
<td>40</td>
<td>68</td>
</tr>
<tr>
<td>B737-500</td>
<td>11</td>
<td>31</td>
<td>53</td>
</tr>
<tr>
<td>B737-800</td>
<td>16</td>
<td>44</td>
<td>76</td>
</tr>
<tr>
<td>B757-200</td>
<td>19</td>
<td>55</td>
<td>94</td>
</tr>
<tr>
<td>B767-300ER</td>
<td>29</td>
<td>81</td>
<td>140</td>
</tr>
<tr>
<td>B747-400</td>
<td>41</td>
<td>117</td>
<td>202</td>
</tr>
<tr>
<td>A319</td>
<td>13</td>
<td>36</td>
<td>62</td>
</tr>
<tr>
<td>A320</td>
<td>15</td>
<td>42</td>
<td>72</td>
</tr>
<tr>
<td>A321</td>
<td>18</td>
<td>51</td>
<td>88</td>
</tr>
<tr>
<td>ATR42-300</td>
<td>4</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>ATR72-200</td>
<td>6</td>
<td>16</td>
<td>28</td>
</tr>
</tbody>
</table>

(Base scenarios. Per-aircraft, per-minute costs in Euros.)

The Royal Institute of Navigation - Aviation's Future Trajectories
Airline delay cost management
Tactical recovery, the Cost Index

Value in FMS

$Cl_0$  
save fuel

$Cl_{\text{max}}$  
save time  
(e.g. recover delay)

§ 2–5 mins/hr; $\Delta_S$: 3–8% (AVG 5%), appx. 20 kt
Dynamic cost indexing

4D control / (tactical) management of delay costs

4D management
- ACARS
- CPDLC
- AIDL
- ICAO?

The Royal Institute of Navigation - Aviation's Future Trajectories
B738, 20 mins at-gate delay / route extension

At-gate, € 1109

Extended cruise, € 1948

Future exploitation potential for slot trade-offs & airspace design. Includes reactionary: different methods for pax, l-h / s-h crew & maintenance.

The Royal Institute of Navigation – Aviation’s Future Trajectories
LIS–HEL, B738 (22 minutes delay)

The Royal Institute of Navigation – Aviation’s Future Trajectories
Annual cost implications, simple example

B738, 22 minutes delay: $C_{I_{opt}}$ compared with $C_{I_{max}}$ (i.e. recover 19 minutes); 20 such flights in network per day

<table>
<thead>
<tr>
<th>Case</th>
<th>Emissions costs</th>
<th>Fuel cost</th>
<th>Optimum recovery</th>
<th>Optimum CI</th>
<th>Annual loss c.f. $C_{I_{300}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>€ 0.7 / kg</td>
<td>10 mins</td>
<td>80</td>
<td>€ 6.7 million</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>€ 0.7 / kg</td>
<td>11 mins</td>
<td>90</td>
<td>€ 4.5 million</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>€ 0.5 / kg</td>
<td>12 mins</td>
<td>130</td>
<td>€ 2.7 million</td>
</tr>
</tbody>
</table>

(Without emissions costs: allows pre-2012 trade-offs.
Lido OC is ACARS-enabled: can send CI proposal to aircraft.)
The Royal Institute of Navigation – Aviation’s Future Trajectories
Technical challenges for 4D

§ “Best business outcome” as goal (Master Plan)
- User-Driven Prioritisation Process: negotiation, CDM, SWIM
- AOs “can among themselves recommend to the Network Management a priority order” for delayed flights (Strategic Guidance, May 2009)
- quantifying prioritisation has been a headache for a long time!
- “cooperative” (AO-CFMU) slot swapping is planned as part of process

§ Aircraft and controller ‘compliance’
- FMS parameters: Required Time of Arrival & Cost Index need to align
- Controlled Time of Arrival in very busy TMA?
- need ICAO recommendations re. 4D definition & data exchange

§ Arrival sequencing / queue management during transition
- mixes of 4D-equipped and non-equipped traffic turn up
- Brooker (Journal of Navigation [62]) & Hansen et al (in progress)
The flow management context
ATFM – slot distribution

Actual distribution, 2008. (NB. 88% IFR flights no ATFM delay.)

€1.5 billion
## ATFM – slot distribution

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>μ</th>
<th>σ</th>
<th>≥60 mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 (actual)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.36</td>
</tr>
<tr>
<td>Simple halving</td>
<td>50</td>
<td>50</td>
<td>72</td>
<td>0.18</td>
</tr>
<tr>
<td>Push to left</td>
<td>51</td>
<td>74</td>
<td>68</td>
<td>0.00</td>
</tr>
<tr>
<td>Push to edges</td>
<td>33</td>
<td>60</td>
<td>53</td>
<td>0.07</td>
</tr>
</tbody>
</table>

(All values are percentages. First three columns, relative.)
# ATFM – slot distribution

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>μ</th>
<th>σ</th>
<th>≥60 mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 (actual)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.36</td>
</tr>
<tr>
<td>Simple halving</td>
<td>50</td>
<td>50</td>
<td>72</td>
<td>0.18</td>
</tr>
<tr>
<td>Push to left</td>
<td>51</td>
<td>74</td>
<td>68</td>
<td>0.00</td>
</tr>
<tr>
<td>Push to edges</td>
<td>33</td>
<td>60</td>
<td>53</td>
<td>0.07</td>
</tr>
</tbody>
</table>

(All values are percentages. First three columns, relative.)
## ATFM – slot distribution

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$\geq60$ mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 (actual)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.36</td>
</tr>
<tr>
<td>Simple halving</td>
<td>50</td>
<td>50</td>
<td>72</td>
<td>0.18</td>
</tr>
<tr>
<td>Push to left</td>
<td>51</td>
<td>74</td>
<td>68</td>
<td>0.00</td>
</tr>
<tr>
<td>Push to edges</td>
<td>33</td>
<td>60</td>
<td>53</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*All values are percentages. First three columns, relative.*
The Royal Institute of Navigation – Aviation’s Future Trajectories
SESAR revisited (KPAs)

Performance objectives and targets for 2020

- departure: 98% of flights departing as planned ±3 min
  other 2%: ATM average delay < 10 min
- arrival: 95% of flights arriving as planned ±3 min
  other 5%: average delay < 10 min
- fuel: 95% of flights fuel as planned ±2.5%
  other 5%: average additional consumption <5%
  NB. new definition of ‘on time’: ≤ |3 mins|
- less variation in the actual block-to-block times
  for repeatedly flown routes using aircraft with comparable performance,
  block-to-block σ < 1.5% of route mean
- less reactionary delay & fewer reactionary cancellations (-50% 2010-2020)
- other KPAs, e.g. for: capacity, flexibility, cost effectiveness, efficiency

The Royal Institute of Navigation – Aviation’s Future Trajectories
Opportunities ahead for time/delay management
Opportunities ahead

§ Development of tools
- integration of 4D tools (e.g. delay cost) with flight planning
- cherry-pick: passenger re-accommodation tools (e.g. Sabre)
- collaborative prioritisation tools interfaced into SWIM (?)
- controller tools (congested airspace – work underway)

§ Development of models (including emissions)
- future use of Cost Index in 4D environment (Clean Sky)
- passenger-centric (new metrics); reactionary effects
- airport-centric models
- ATFM slot distributions (feasibility), cost-focused
Thank you
Stand-by slides
SESAR’s three ATM frameworks

§ **Performance Framework**
- Concept of Operations is performance-based (as ICAO)
- drives management decisions
- focused on Key Performance Areas (KPAs)

§ **Business Framework**
- establishes stakeholder partnerships
- establishes shared network targets & priorities
- implements the “Business Trajectory”

§ **Institutional and Regulatory Framework**
- member states remain responsible for enforcement
- adapting to business & societal changes
Aircraft performance

The cruise-level performance envelope is between $V_{MU}$ and $V_{MO}$, with a range of $\pm 4\%-7\%$.
Airspace procedures

§ Speed control, in European context
- used in TMAs (usually with heading & altitude constraints)
- very seldom used en route (various studies on this, although not our focus)

§ Evidence suggests
- controllers used to +3% to −6% (mostly ±3%)
- use of ICAO* > ±5% rule, “inadvertent changes” = rather unclear

Three key trade-off stages

§ Buffers in schedules *(strategic cost of delay!)*
  – large enough to absorb expected levels of tactical delay
  – avoid over-compromising utilisation

§ Slot management *(pre-departure, tactical)*
  – re-route potential
  – fuel uplift decision

§ Airborne recovery *(tactical)*
  – focus of project to date

weather (esp. wind, ABN)
ATC / ATM cooperation
Tactical recovery, the Cost Index

benefit / profitability

punctuality

The Royal Institute of Navigation – Aviation’s Future Trajectories
### Reactionary multipliers

<table>
<thead>
<tr>
<th>Range (mins):</th>
<th>1-15</th>
<th>16-30</th>
<th>31-45</th>
<th>46-60</th>
<th>61-75</th>
<th>76-90</th>
<th>..</th>
<th>300+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>1.48</td>
<td>1.74</td>
<td>2.00</td>
<td>2.25</td>
<td>2.51</td>
<td>2.77</td>
<td>..</td>
<td>6.47</td>
</tr>
<tr>
<td>Additional rotational</td>
<td>0.36</td>
<td>0.56</td>
<td>0.75</td>
<td>0.94</td>
<td>1.13</td>
<td>1.32</td>
<td>..</td>
<td>4.11</td>
</tr>
<tr>
<td>Additional non-rotational</td>
<td>0.12</td>
<td>0.19</td>
<td>0.25</td>
<td>0.31</td>
<td>0.38</td>
<td>0.44</td>
<td>..</td>
<td>1.37</td>
</tr>
</tbody>
</table>

(Average value in each range.)

Different methods for passenger, long-haul crew, short-haul crew and maintenance costs.
Emissions (a future cost)

§ No global agreement on aviation regarding emissions
  - regional competitive distortion; focus on Copenhagen (December 2009)

§ % of anthropogenic GHGs: various estimates, agree increasing
  - 3.4% in Europe (European Environment Agency, 2006)
  - 1.6% global; ‘CO$_2$+’ $\approx$ 5% of warming by 2050 (Stern Review, 2007)

§ ATM accounts for 0.2% of CO$_2$ emissions in the EU

§ CO$_2$ (warming effect; proportional to fuel burn)
  - EU ETS: extending to aviation (01 JAN 12) based on gate-to-gate fuel
  - legislation currently: all AOs operating to/from EU surrender permits

§ NO$_x$ (NO & NO$_2$: warming effect [O$_3$] & cooling effect [CH$_4$])
  - Commission pledged aviation proposal by November 2009
CO\textsubscript{2}: illustrative impact of EU ETS
CO$_2$: illustrative impact of EU ETS

simple: 4% p/a

The Royal Institute of Navigation – Aviation’s Future Trajectories
CO$_2$: illustrative impact of EU ETS

Aviation joins ETS near end of 2$^{nd}$ TP (01 JAN 12)

Aviation permits capped @ 97% c.f. 2004-06

The Royal Institute of Navigation – Aviation’s Future Trajectories
CO$_2$: illustrative impact of EU ETS

Reducing caps ...

- 2005: 'free'
- 2012: internal auction, 97%
- 2013: free, 95%
- 2020: external purchase

The Royal Institute of Navigation – Aviation’s Future Trajectories
CO\textsubscript{2}: illustrative impact of EU ETS

Some sectors: auction 70% (of cap) by 2020

The Royal Institute of Navigation – Aviation’s Future Trajectories
Delay cost management

- Many airlines have significant barriers to identifying & quantifying delay costs, even before managing them
- General lack of tools for delay cost management
- Lack of integration & standardisation of existing tools
- Aircraft & crew often recovered first, respecting maintenance requirements - rarely driven by passenger solutions

Generally, in the disruption management literature passengers are given a low priority.

Kohl et al. (2007)

In most airlines … two groups doing their individual best could actually be working against each other.

Narasimhan (2001)
Effects of cost index settings on emissions

§ Compared 3 operational flight plans at min/max CI

– comparison of time savings at higher CI
– comparison of costs for CO₂ and NOₓ
– costs shown for illustration only, to nearest Euro
– used: CO₂ at € 37 / tonne; NOₓ at € 6 414 / tonne (2012)
– values depend on policy design & implementation - estimates vary

§ For NOₓ derived relative measure of radiative forcing

– only fuel consumption > 3000 ft used (for LAQ use kg < 3000 ft)
– takes into account aircraft type and route length
– altitude dependence of radiative impact considered
Passenger costs of delay to the airline

§ Ideally need dynamic data for each passenger, although in practice historical estimates may be better

§ Regulation (EC) 261 (17 February 2005); airline policy

§ ‘Soft’ cost model [starting from 2003 estimate of average]
  – very little published; very few airlines have assessed
  – model used (own) surveys; complaints rates and disutility models

§ ‘Hard’ cost model [starting from 2003 estimate of average]
  – model used (own) surveys, limited airline data & literature
  – ‘care’: drink/meal vouchers, hotel accommodation etc
  – ‘reaccommodation’: rebooking/rerouting (/reimbursements)

theoretical distribution, subject to several known constraints