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4D trajectories - assessing the cost of time

Cook, A.J.

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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

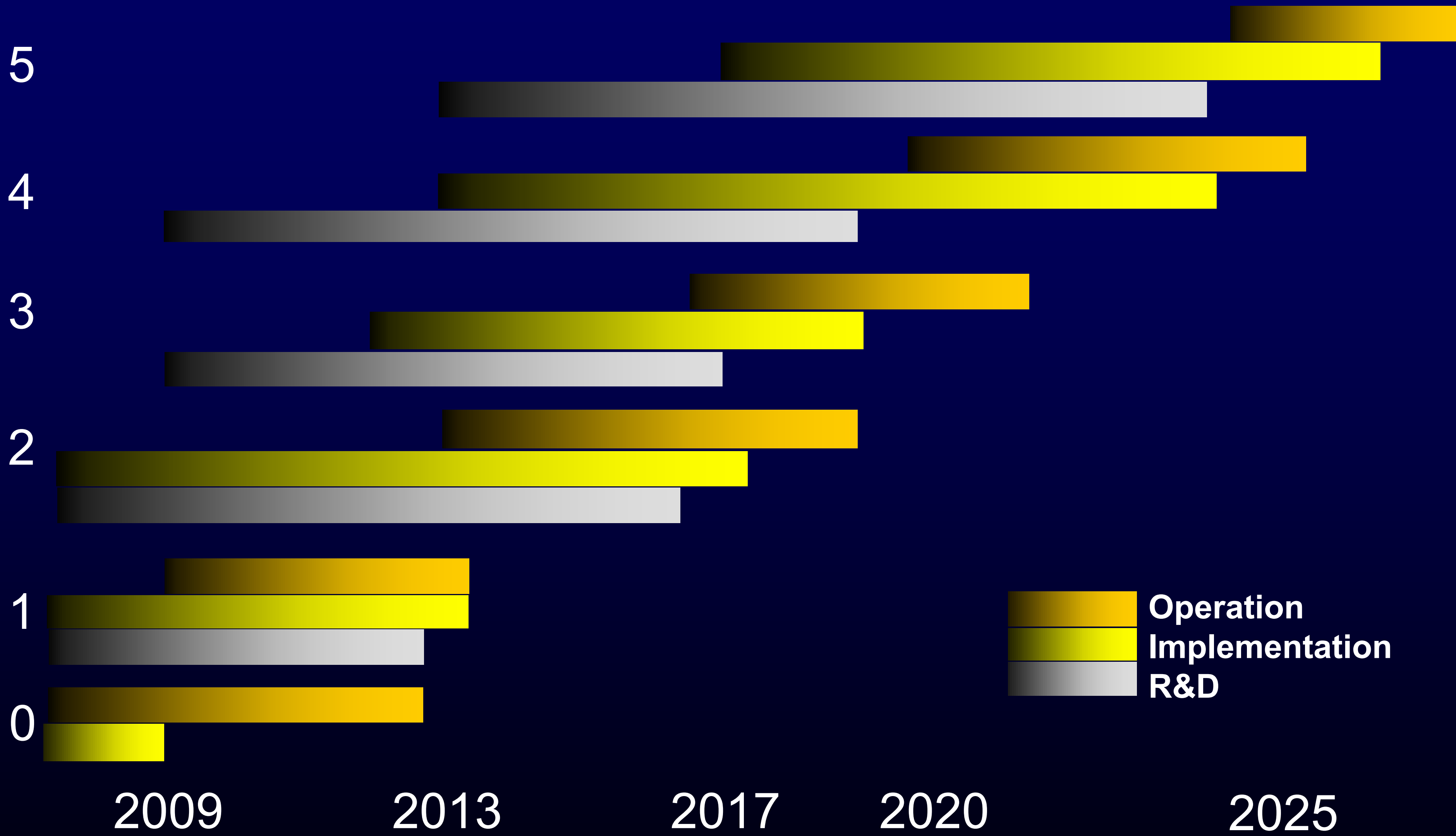
The Business (4D) Trajectory

- 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)

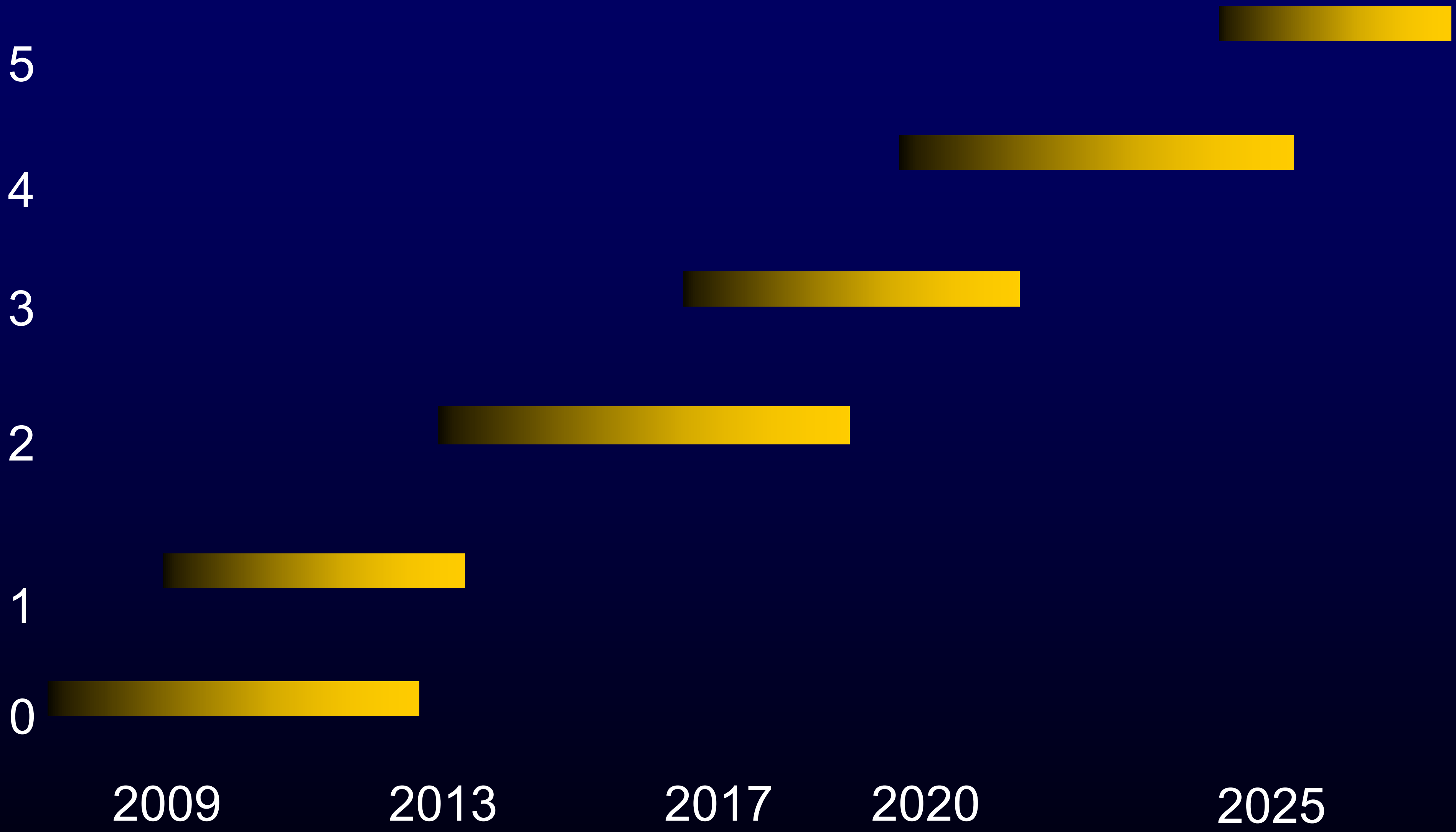
  Negotiation complete: trajectory which airline agrees to fly and ANSP + airport agree to provide; c.f. current practice, from both providers and users, of pre-tactical and tactical changes: new concept designed to minimise changes to trajectories & achieve 'best business outcome' for all users
- A key business outcome is reduction of delay
- Matures through 'Service Levels' delivered …

The six Service Levels (0-5)



Source: European ATM Master Plan (2009) (approximately to scale)

The six Service Levels (0-5)



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 six Service Levels (0-5)

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

Navigation News

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 <u>minutes</u> of delay to <u>cost</u> of delay

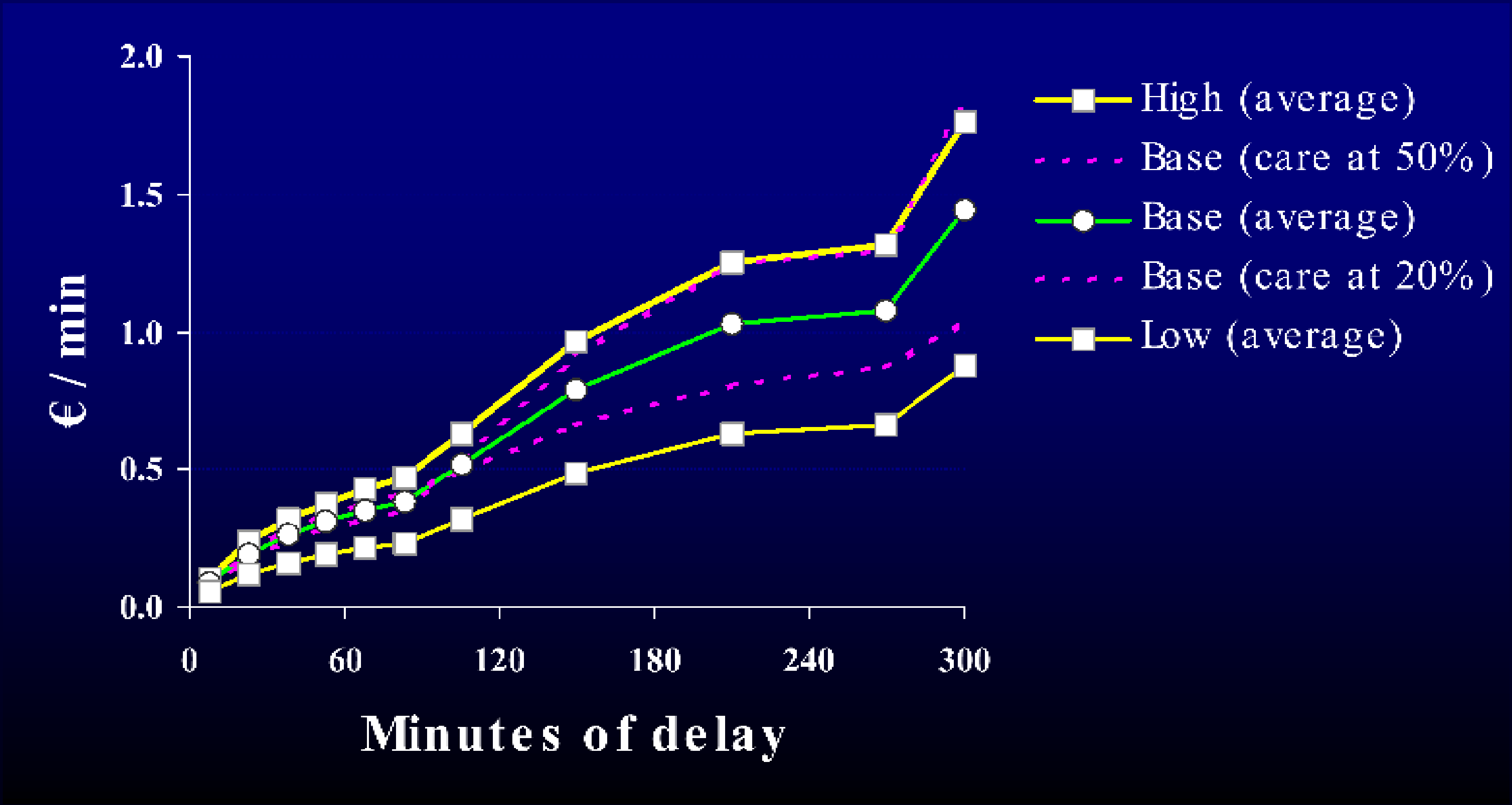
B733, B734, B735, B738, B752, A319, A320, A321, AT43, AT72; B747, B763

Quantifying the cost of time (delay) to an airline

Delay cost model & magnitudes

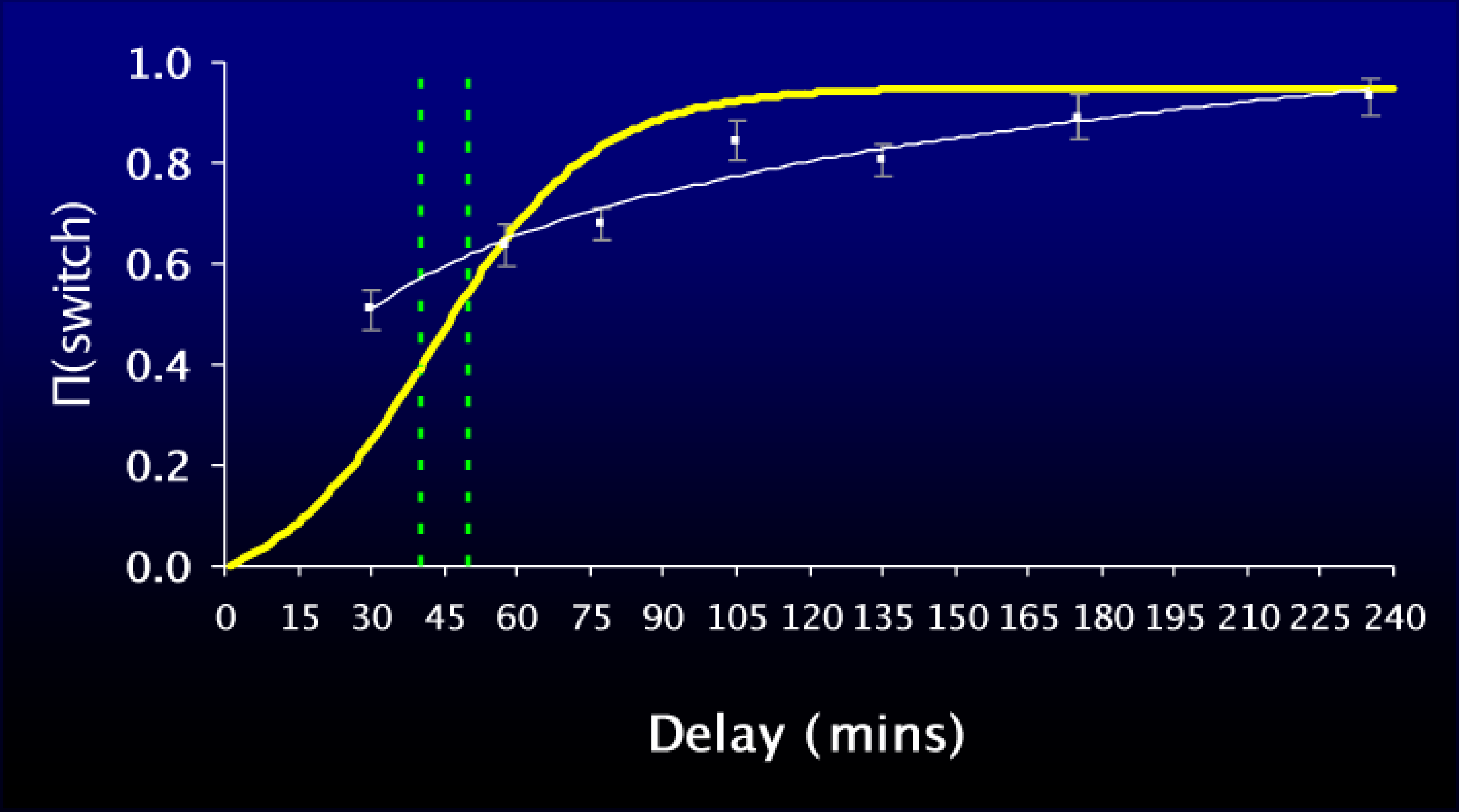
- Airport charges and handling fees
  - e.g. hit or miss peak charge; penalty from an agent
- Maintenance
  - extra minutes of wear & tear on airframe & powerplants
  - gate-to-gate (workload) model for marginal costs
  - line/transit + A, C & D checks (- overheads) converted to hours basis
- Crew
  - 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; CO_2/tonne: €0.03 - €30 (€13 - Nov 09)
- Passenger costs: AO ‘hard’ + AO ‘soft’ (+ ‘internalised’) …

Passenger costs of delay to the airline



'Hard' cost model, with sensitivity analysis

Passenger costs of delay to the airline



'Soft' cost model included Kano satisfaction modelling

Passenger costs of delay to the airline

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

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

Airline delay cost management

Tactical recovery, the Cost Index

Value in FMS

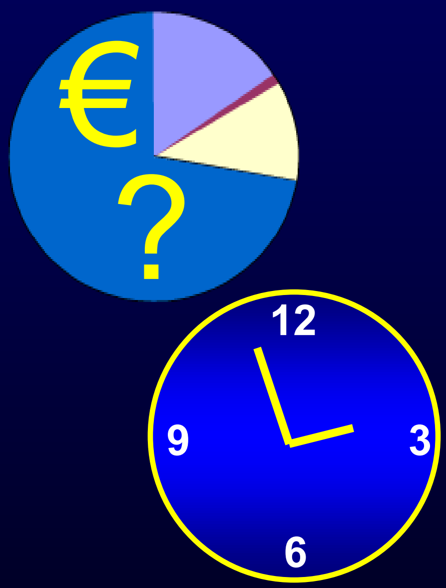
CI_0 save fuel

CI_{max} save time

(e.g. recover delay)

§ 2–5 mins/hr; Δ_S: 3–8% (AVG 5%), appx. 20 kt

Dynamic cost indexing



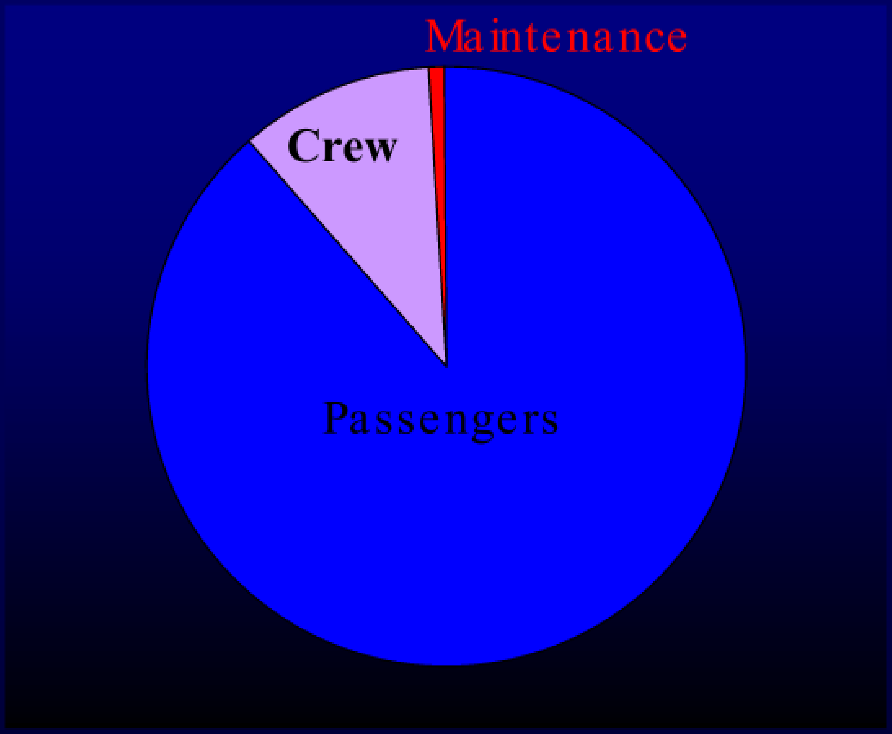
4D management

↔

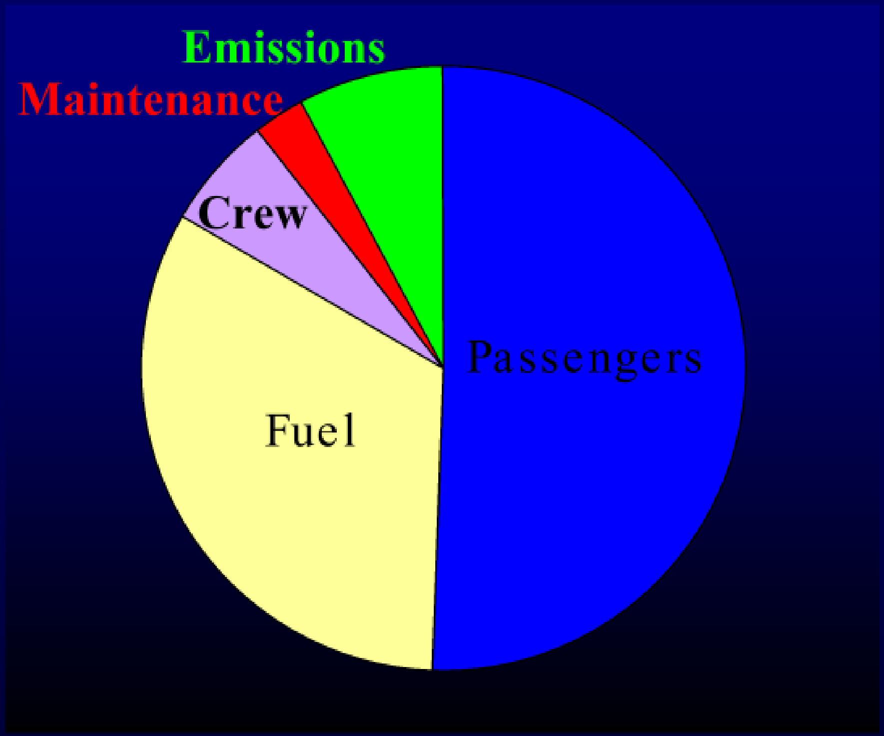
ACARS
CPDLC
AIDL
ICAO?

4D control / (tactical) management of delay costs

B738, 20 mins at-gate delay / route extension



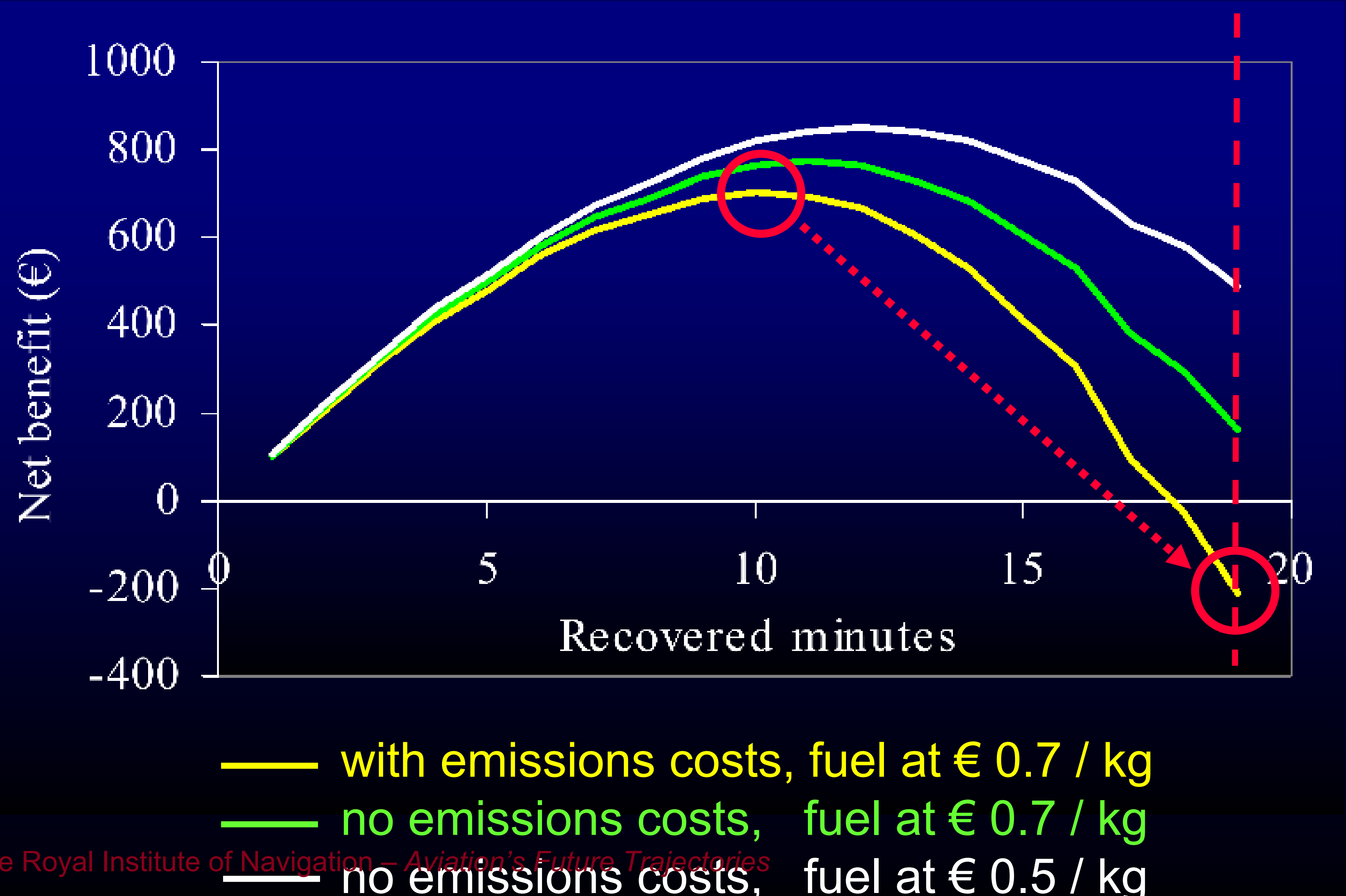
At-gate, € 1109



Extended cruise, € 1948

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

LIS–HEL, B738 (22 minutes delay)

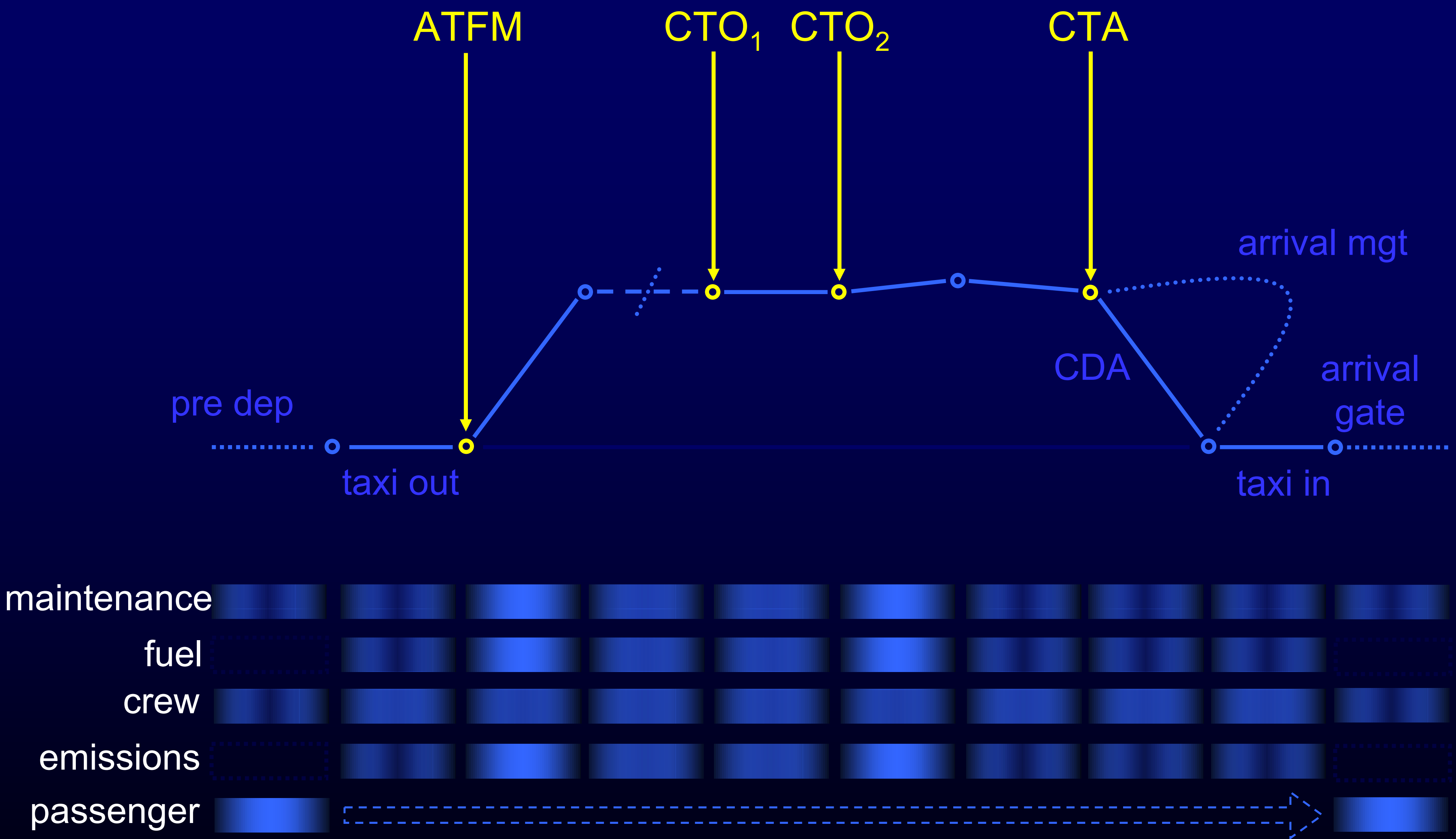


Annual cost implications, simple example

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

Case	Emissions costs	Fuel cost	Optimum recovery	Optimum CI	Annual loss c.f. CI_{300}
1	Yes	€ 0.7 / kg	10 mins	80	€ 6.7 million
2	No	€ 0.7 / kg	11 mins	90	€ 4.5 million
3	No	€ 0.5 / kg	12 mins	130	€ 2.7 million

(Without emissions costs: allows pre-2012 trade-offs.
Lido OC is ACARS-enabled: can send CI proposal to aircraft.)

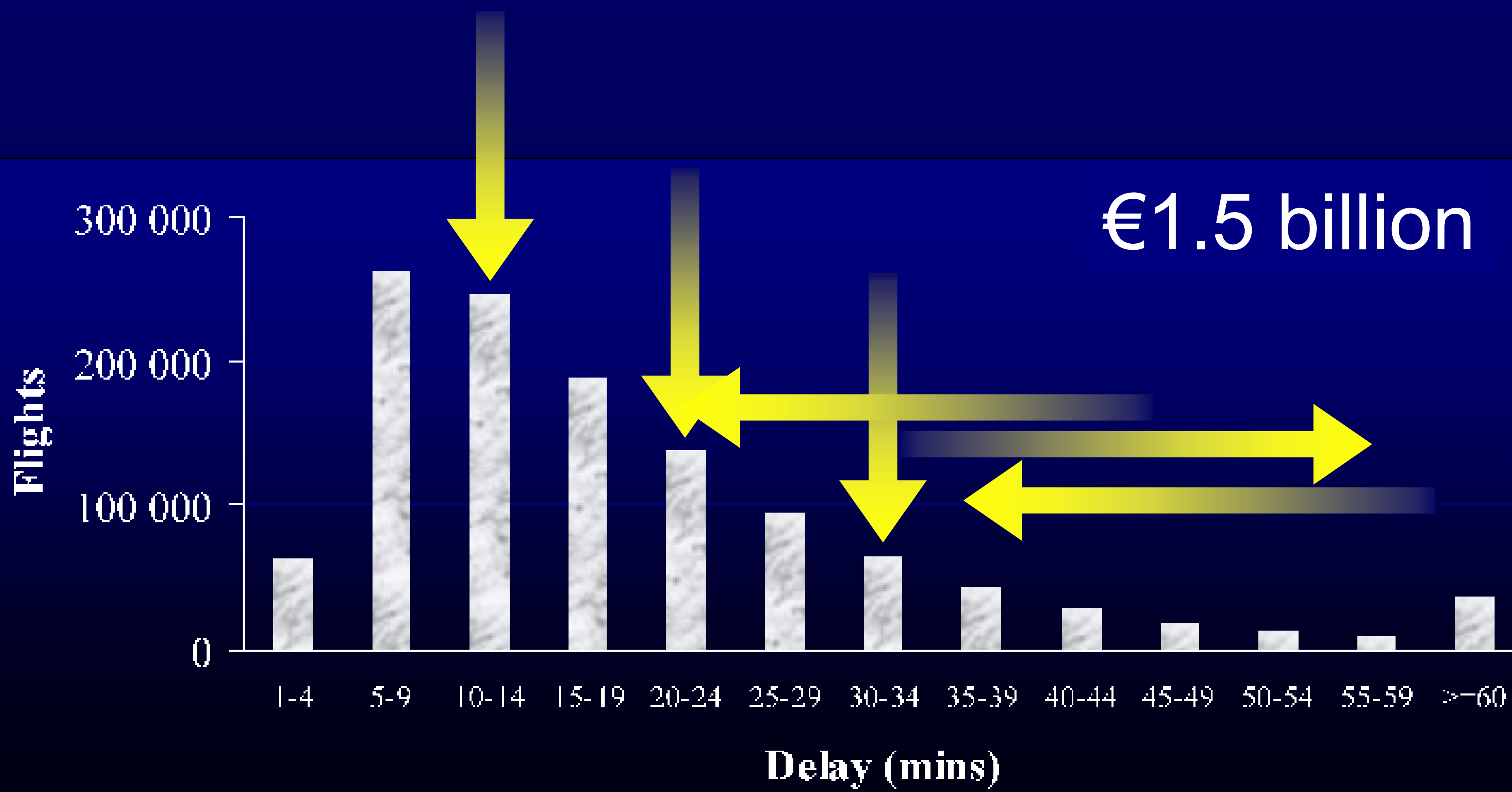

ATFM
CTO1
CTO2
CTA
arrival mgt
CDA
arrival gate
pre dep
taxi out
taxi in
maintenance
fuel
crew
emissions
passenger

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.)

ATFM – slot distribution

	Cost	μ	σ	≥60 mins
2008 (actual)	100	100	100	0.36
Simple halving	50	50	72	0.18
Push to left	51	74	68	0.00
Push to edges	33	60	53	0.07

(All values are percentages. First three columns, relative.)

ATFM – slot distribution

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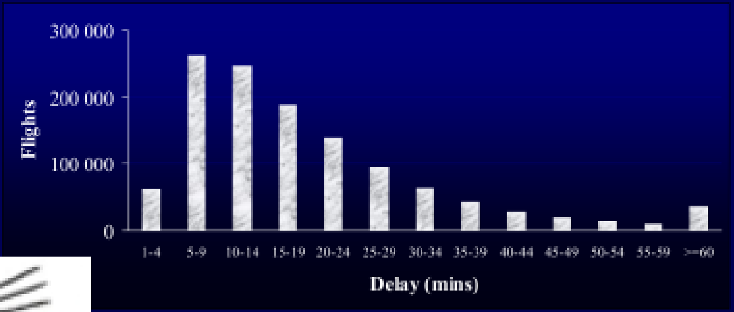

300 000
200 000
100 000
0
Flights
1-4
5-9
10-14
15-19
20-24
25-29
30-34
35-39
40-44
45-49
50-54
55-59
>=60
Delay (mins)


ATFM

?

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

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

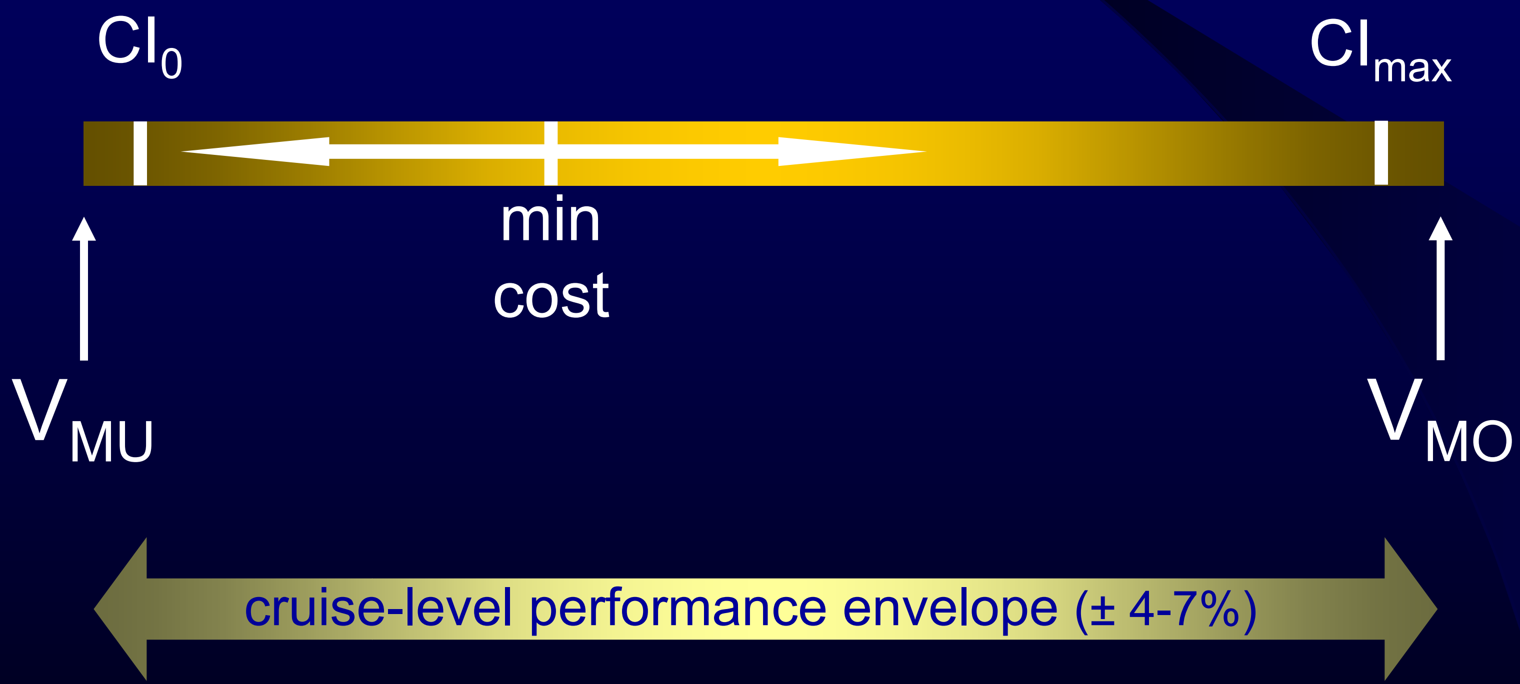
Thank you

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



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

* Rules of the Air, Annex 2 to the Convention of International Civil Aviation (1990)

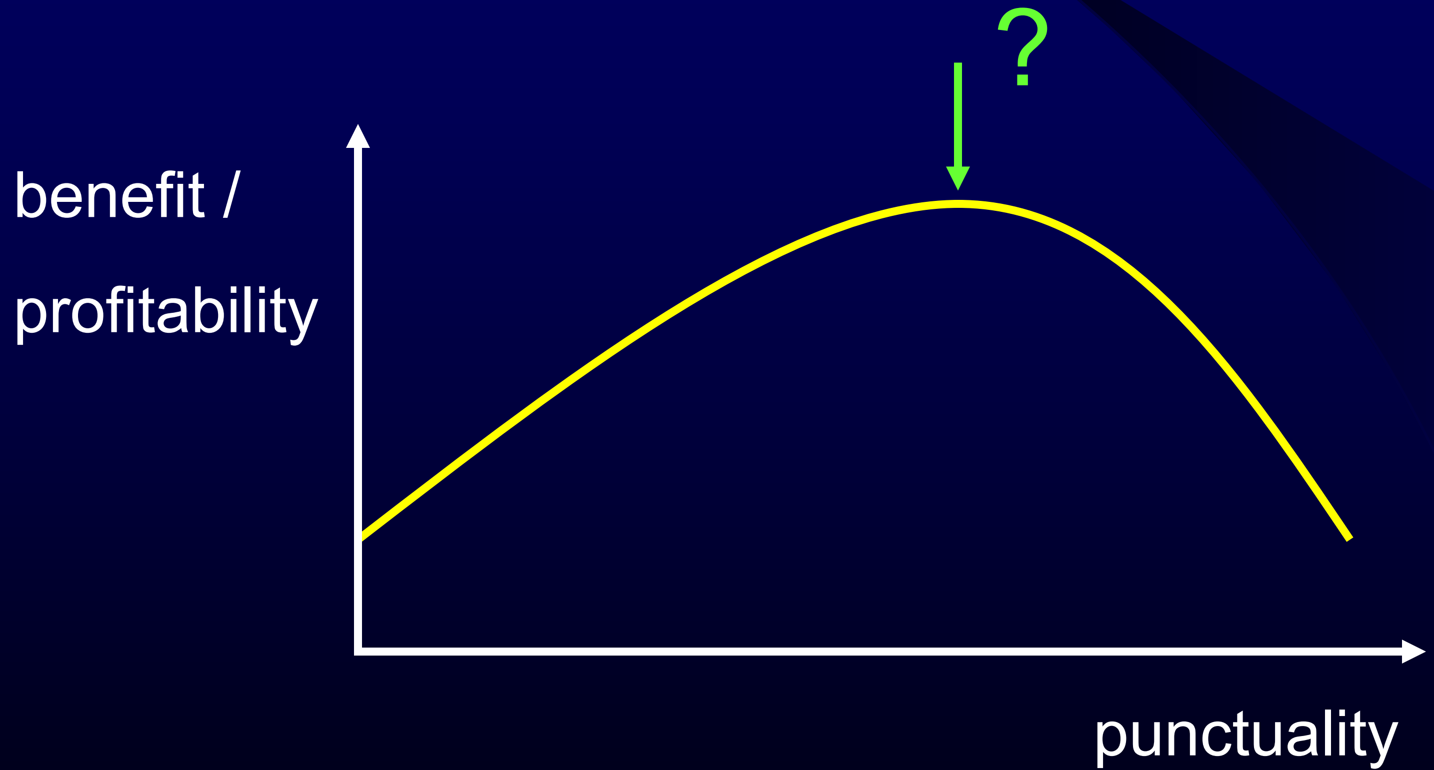
Three key trade-off stages

- 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



Reactionary multipliers

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

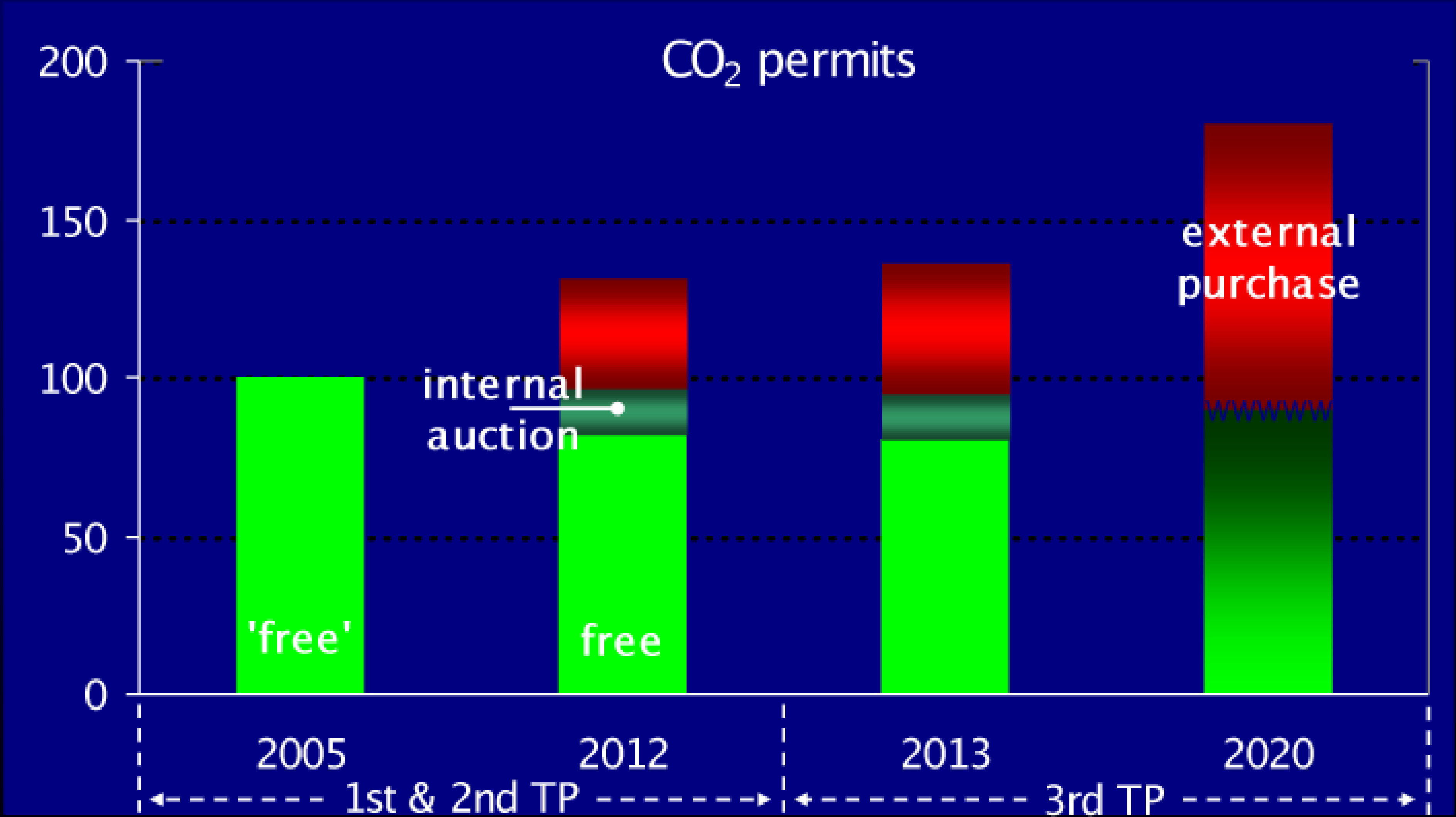
(Average value in each range.)

Different methods for passenger, long-haul crew, short-haul crew and maintenance costs.

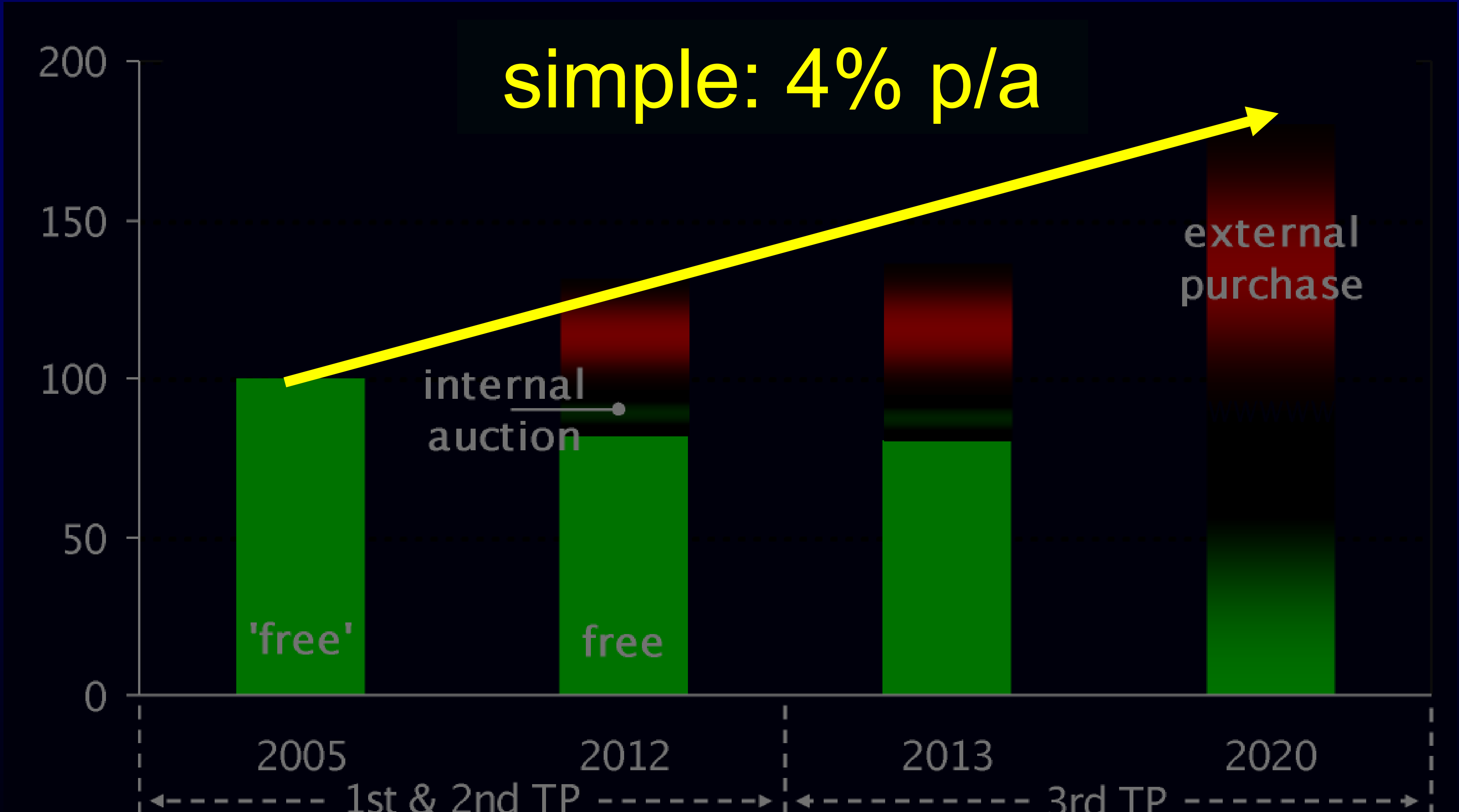
Emissions (a future cost)

- 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+’ ≅ 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

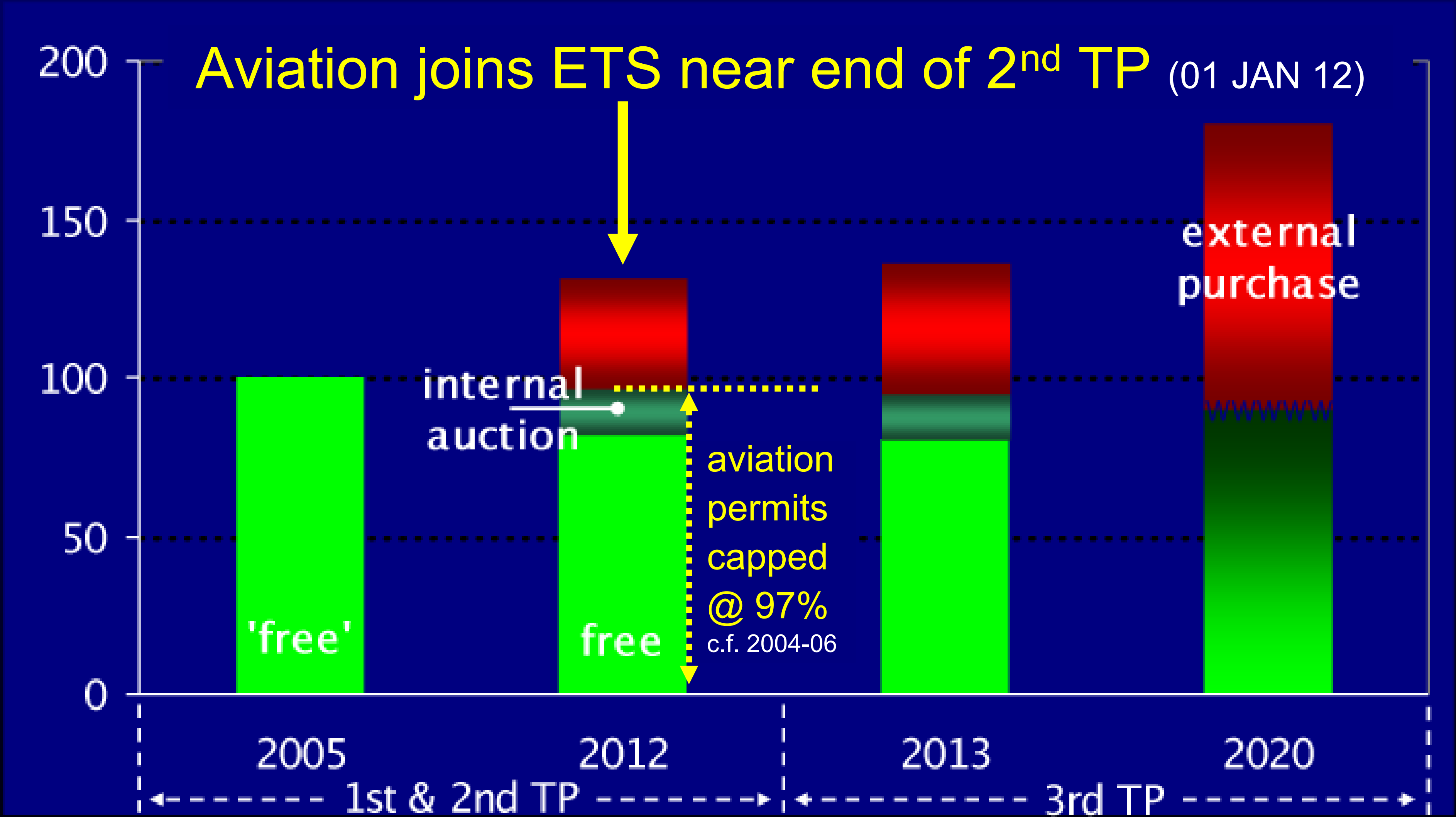
CO_2: illustrative impact of EU ETS



CO_2: illustrative impact of EU ETS



CO_2: illustrative impact of EU ETS



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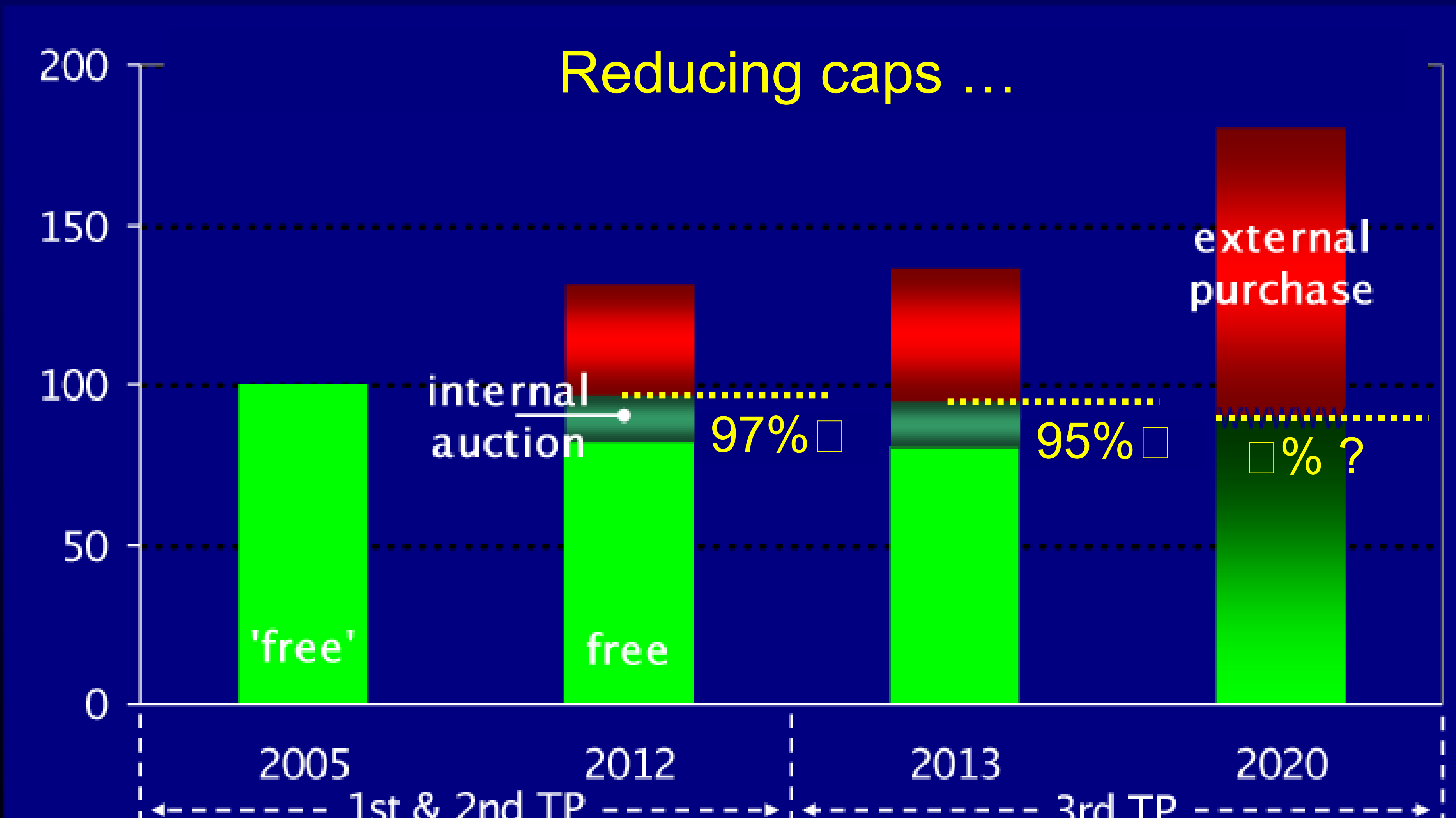

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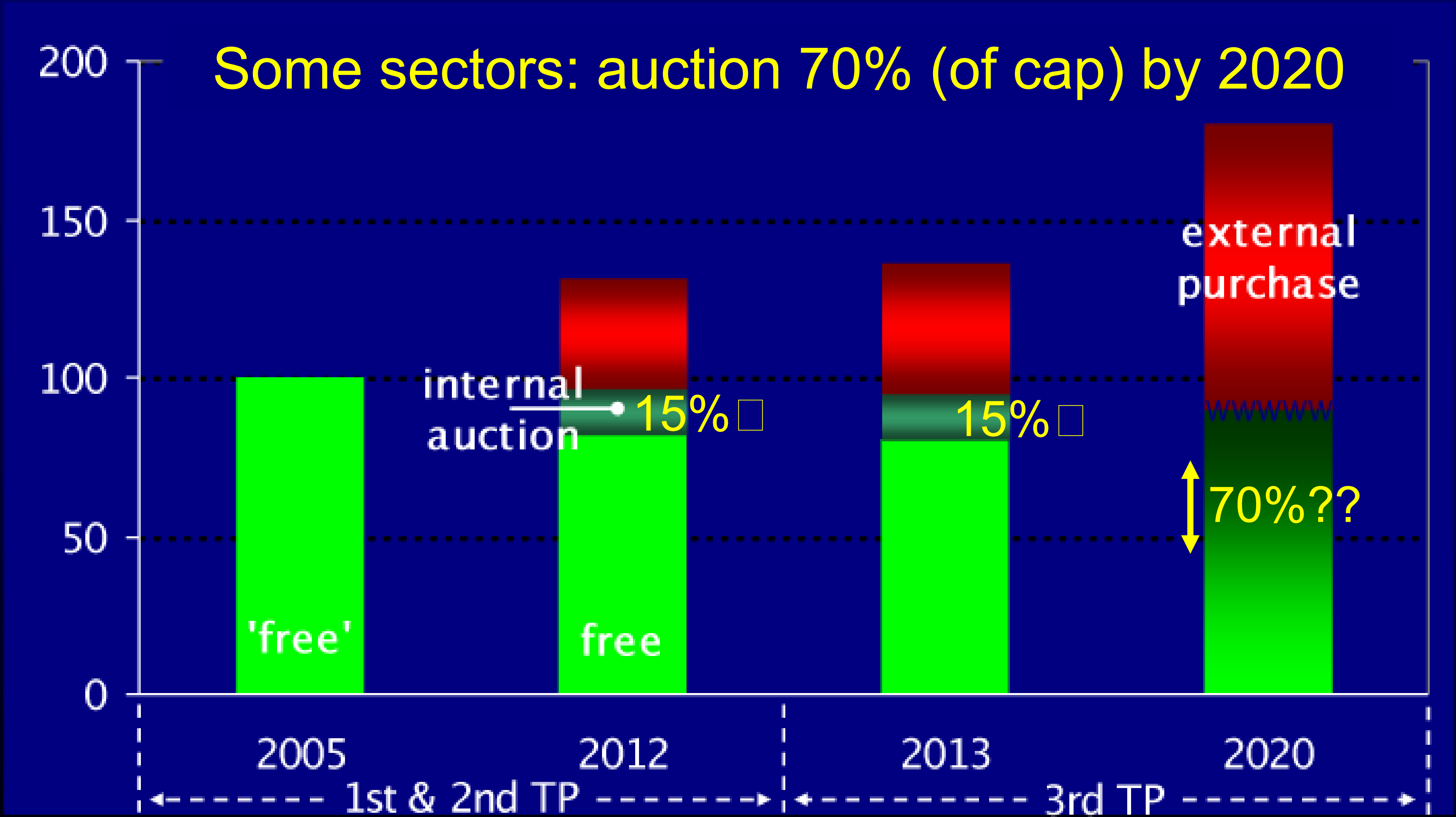


Delay cost management

- 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)

MASTER VIEW for flight LH9999 on route LISHEL2 — Dynamic Cost Indexing module (prototype)

☑ Dynamic | LH9999
IN | OUT | B738
OFF | ON | LISHEL2

Cost index 'cost of time': total arrival delay costs per minute for given delay bands. This table is read-only. See below to change settings.

1-15 mins	16-30 mins	31-45 mins	46-60 mins	61-75 mins	76-90 mins	91-119 mins	120-179 mins	180-239 mins	240-299
€ 30 /min	€ 73 /min	€ 137 /min	€ 230 /min	€ 343 /min	€ 452 /min	€ 623 /min	€ 1009 /min	€ 1365 /min	€ 1722 /i

NON-PASSENGER delay costs

Departure delay costs [LIS]	Arrival delay costs [HEL]		Airborne costs
€5.8 /min	€5.8 /min	Flight crew	€5.8 /min
€2.8 /min	€2.8 /min	Cabin crew	€2.8 /min
€000 /min — Airport/gate	€000 /min — Airport/gate		€2.8 /min — Maintenance
€0.4 /min — Maintenance	€000 /min — Other		€000 /min — Other

€0.037/kg — CO_2

€6.414/kg — NO_x

Fuel settings

CI settings

PASSENGER & NETWORK delay costs

Select required method

◉ Use own data ...

Default

External

◉ by each connecting flight / ○ use average costs for LH9999

Passenger costs (total) for delaying flights below. Soft costs are [ON].

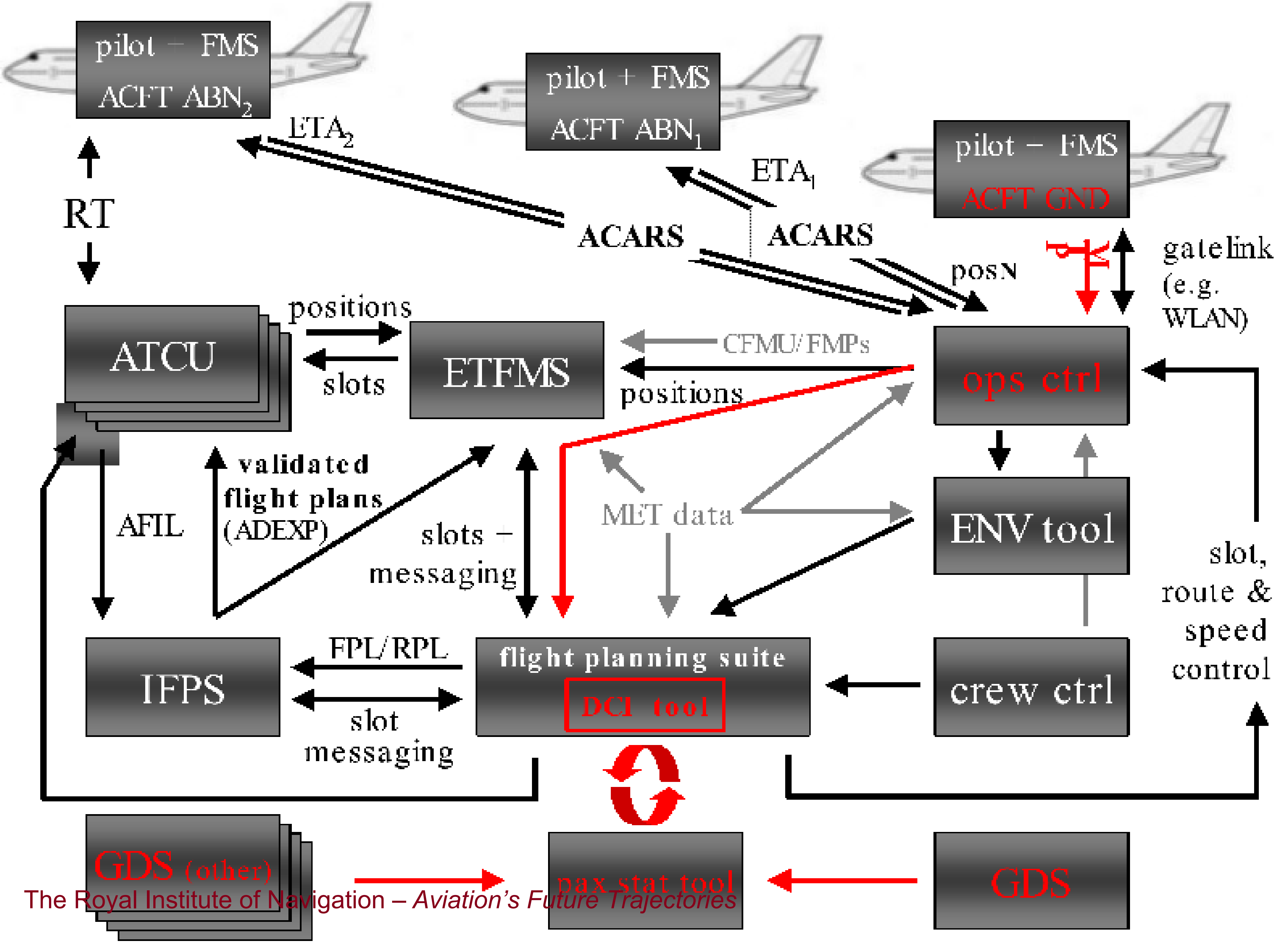
Flight	Aircraft	Reactionary	0€-buffer	Tot pax	1-15 mins	16-30 mins	31-45 mins
LH1111	B733	☐	0 mins	95	€ 98	€ 796	€ 2265
LH2222	B734	☐	0 mins	109	€ 112	€ 909	€ 2586
LH3333	B735	☐	0 mins	85	€ 87	€ 709	€ 2015
LH4444	B738	☐	0 mins	121	€ 124	€ 1010	€ 2871

Reactionary costs: ☐ Include; ☐ At-gate; ☐ Arrival delay; 100%

Soft costs: ☑ Include; Settings

Manage real-time departures data / view connecting passengers

Cancel | OK | Help | Close | TDD


pilot – FMS
ACFT ABN2
pilot + FMS
ACFT ABN1
pilot – FMS
ACFT GND
ETA2
ETA1
RT
ACARS
ACARS
posN
gatelink
(e.g.
WLAN)
ATCU
positions
slots
ETFMS
CFMU/FMPs
positions
ops ctrl
validated
flight plans
(ADEXP)
AFIL
slots +
messaging
MET data
ENV tool
slot,
route &
speed
control
IFPS
FPL/RPL
slot
messaging
flight planning suite
DCI tool
crew ctrl
GDS (other)
pax stat tool
GDS

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 CO_2 and NO_x
  - costs shown for illustration only, to nearest Euro
  - used: CO_2 at € 37 / tonne; NO_x at € 6 414 / tonne (2012)
  - values depend on policy design & implementation - estimates vary
- For NO_x 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