Study on Traffic Synchronization

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Airspace Congestion

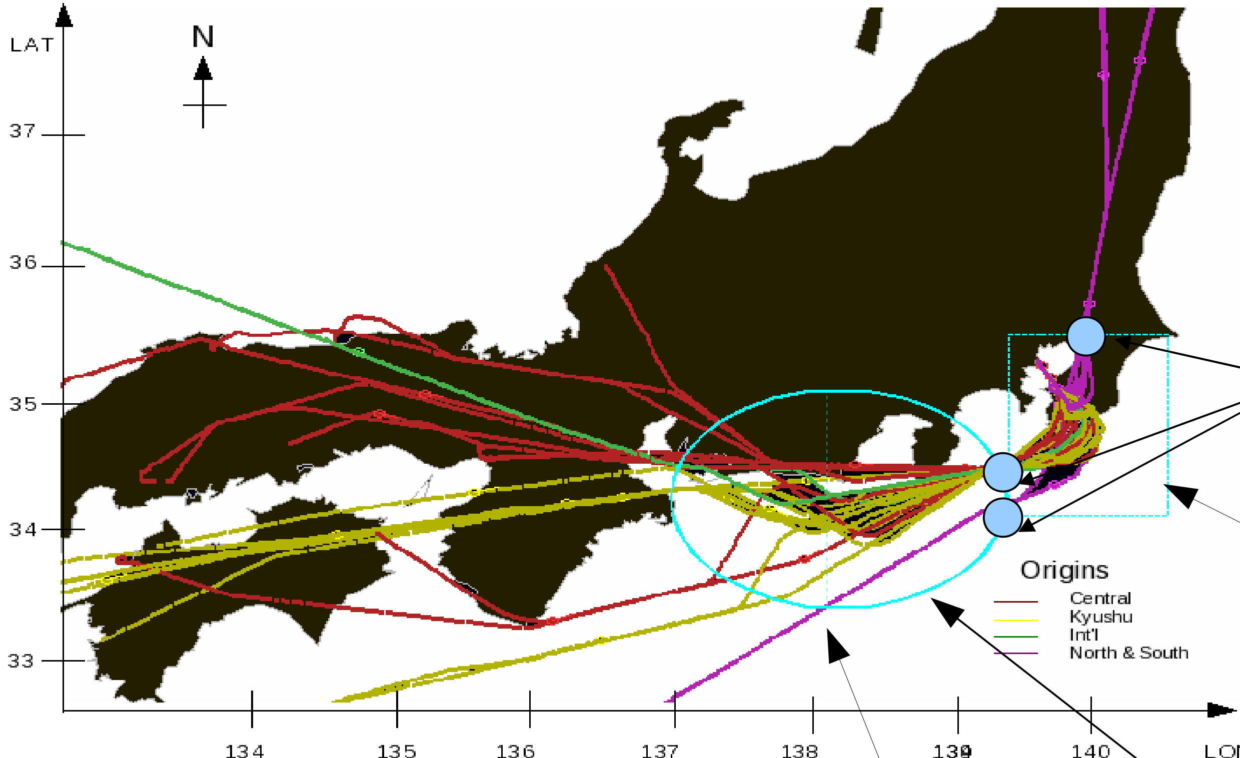
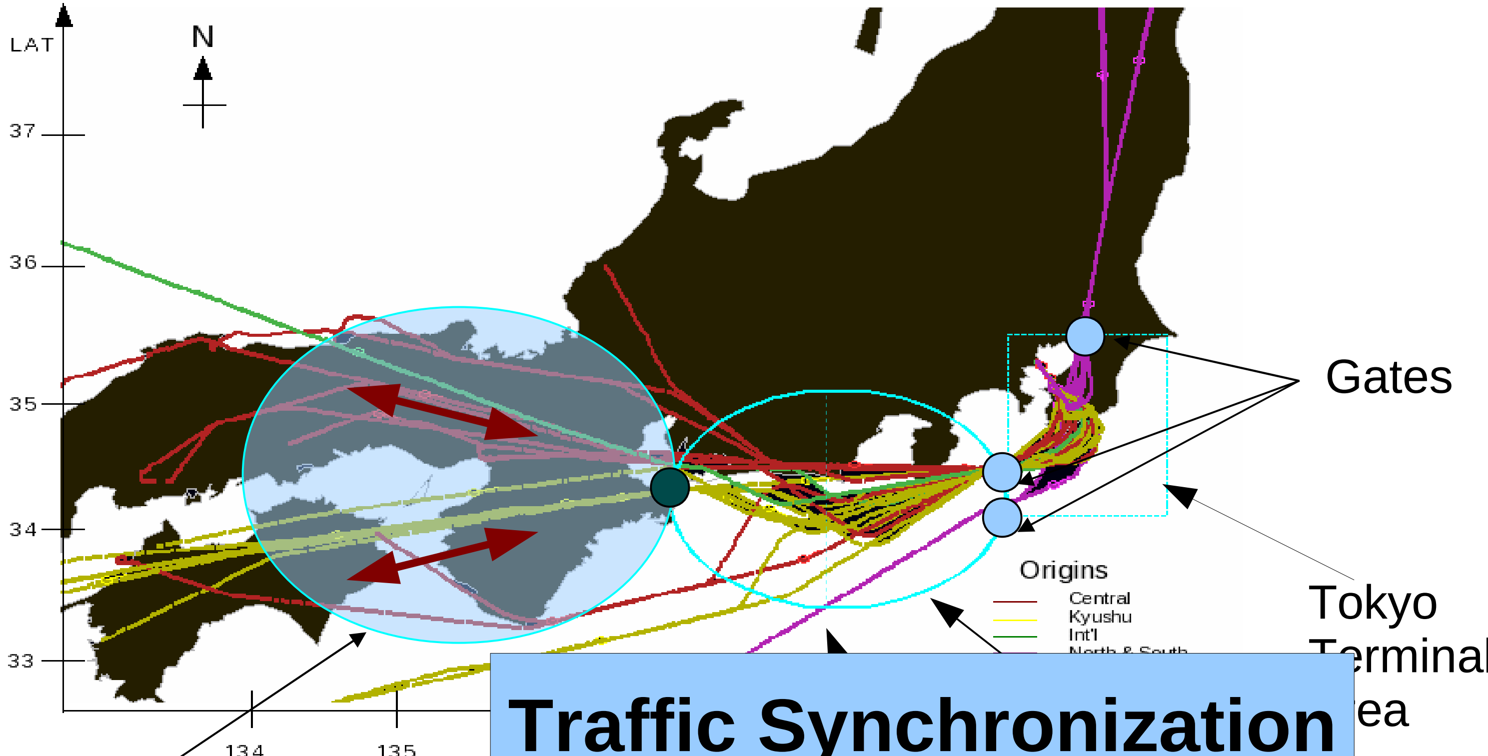


Figure: Inefficient arrival flow to Tokyo Int'l Airport

- Delay
- Fuel consumption
- Controller workload

1. Traffic Synchronization

Airspace Congestion



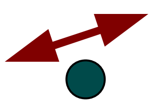
Traffic Synchronization

Definition: “Tactical establishment and maintenance of a safe, orderly and efficient flow of air traffic.” [ICAO]

Benefits:

- Less delay
- Less fuel consumption
- Less controller workload

[ICAO 2005, SESAR, NextGen]

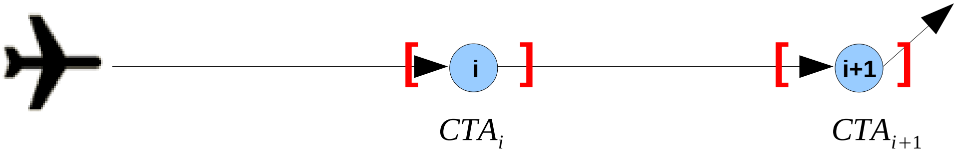


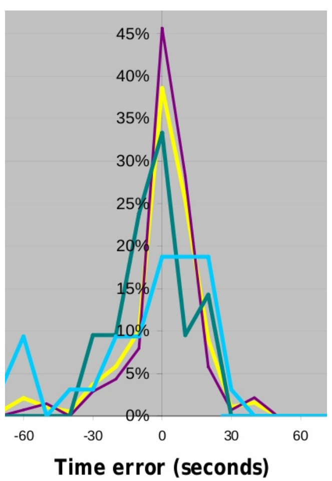
Speed control
Dynamic Queues

Balance ground and en-route delays

Concept of Operations

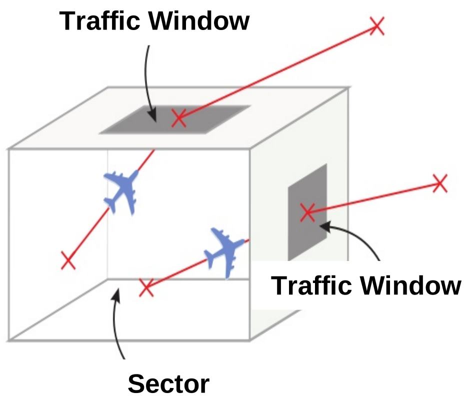
"Controlled time of arrival" (CTA)





Target precision:
+/- 10 sec

Current precision:
+/- 30 sec



Window size:
[cta-x, cta+x] sec

Window position:
- between sectors
- on waypoints
- on merge-points
- (...)

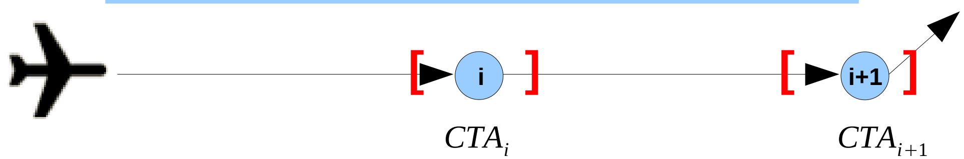
<u>Flight Trials</u>:
CTA/ATC system integration studies (CASSIS)

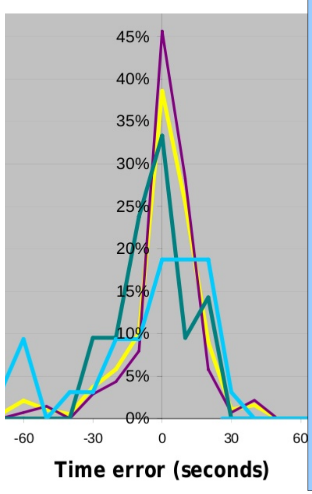
<u>Simulation studies:</u>
Contract-based Air Transportation System project (CATS)

[CASSIS 09, CATS 08]

Concept of Operations

“Controlled time of arrival” (CTA)





Open questions

- Feasibility ?
- Number of constraints ?
- Impact of uncertainty

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Flight Trials:
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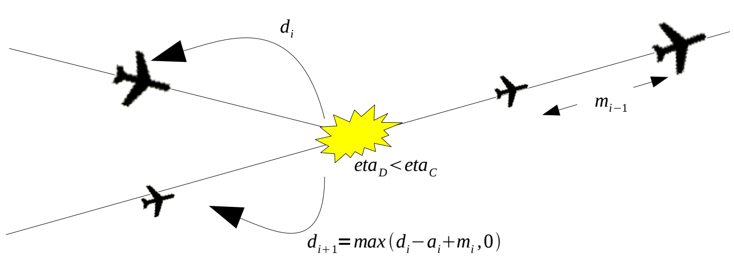
[CASSIS 09, CATS 08]

Delay Propagation

under uncertainties



	Follower	
Leader	Heavy	Mid/Small
Heavy	90	120
Mid/Small	60	60

Aircraft	eta	sta	delay
A	12:01	12:01	0
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D	12:04	12:05	1
C	12:05	12:07	2

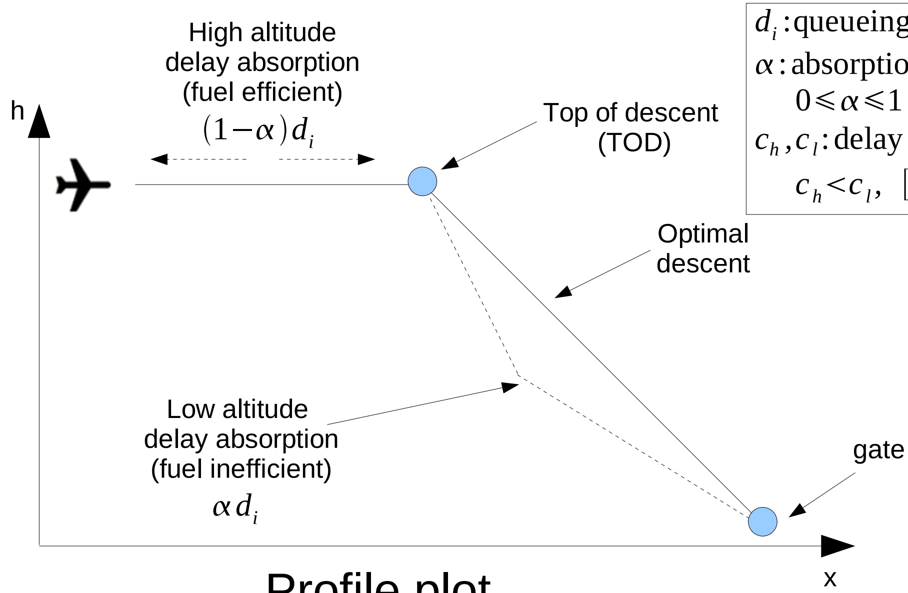
Queueing Delays

[Erzberger 95, Bayen 06, Balakrishnan 09]

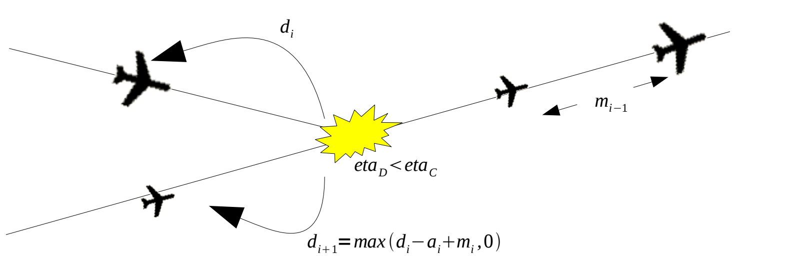
Delay Propagation

under uncertainties

d_i : queueing delay of aircraft i
α : absorption coefficient
$0 \leqslant \alpha \leqslant 1$
c_h, c_l : delay absorption costs
$c_h < c_l$, $[min^{-1}]$



Profile plot



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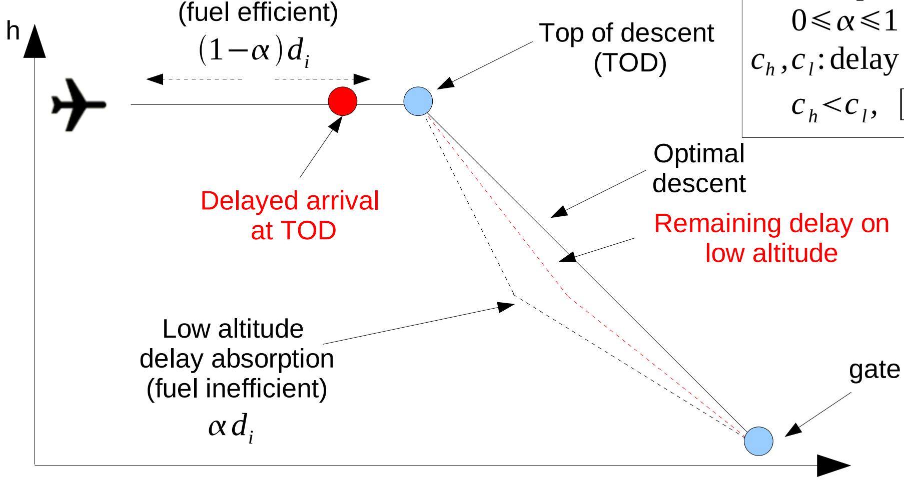

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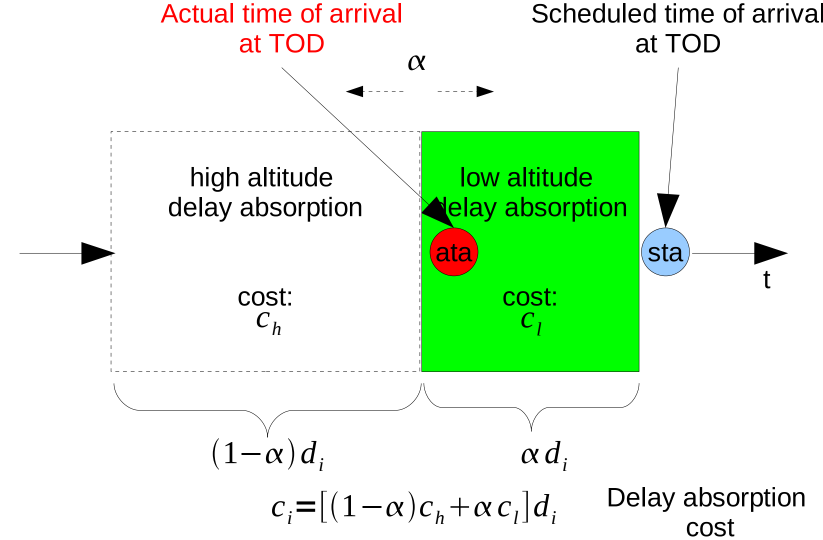
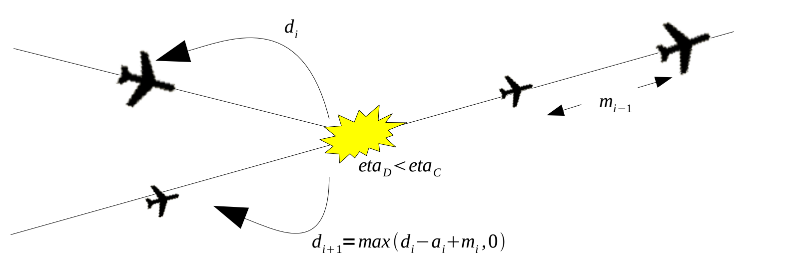


Time plot



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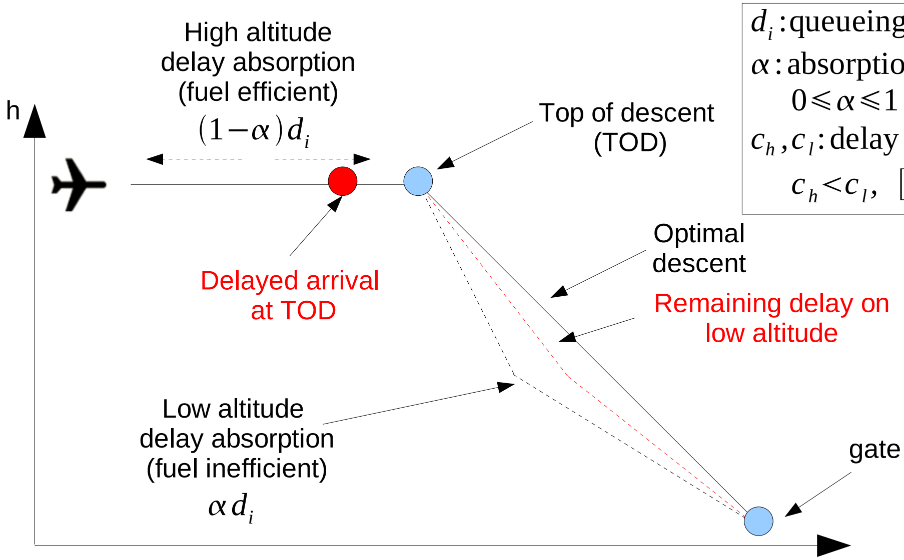

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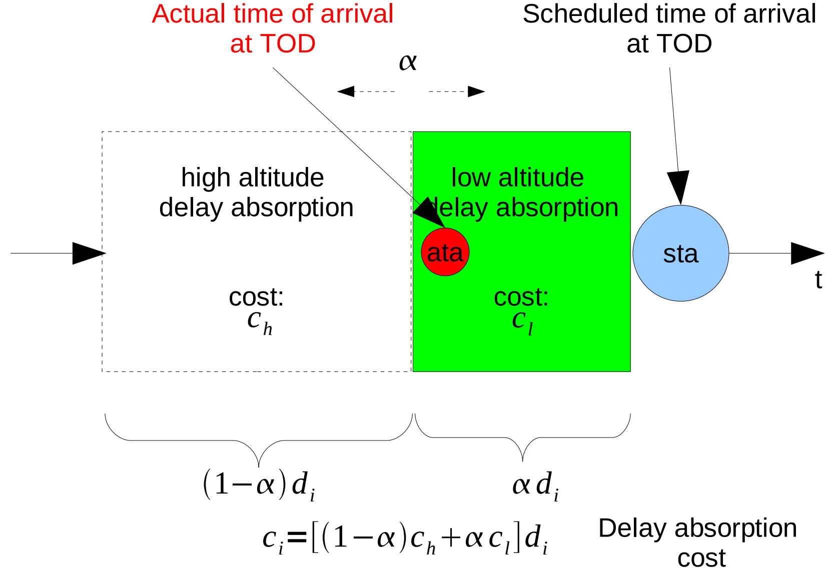

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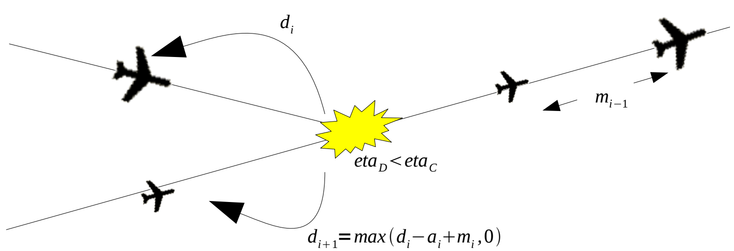

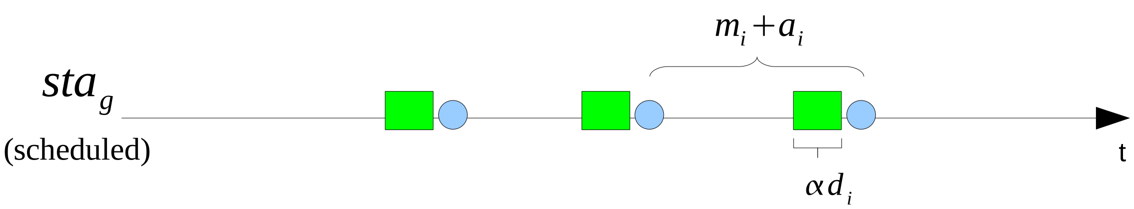

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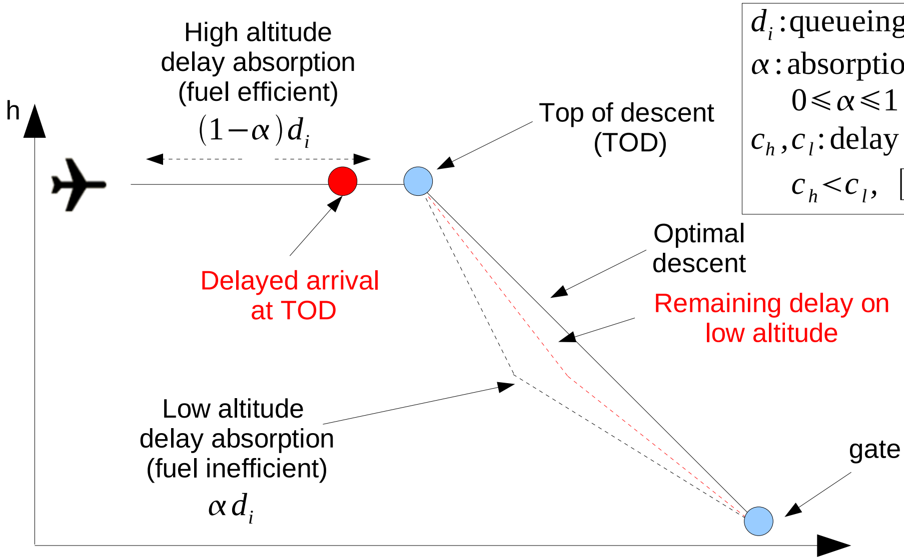

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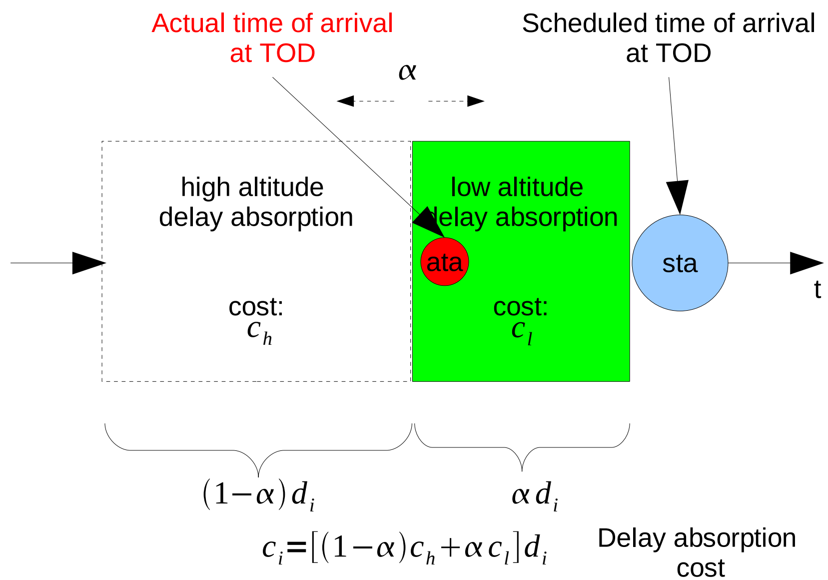

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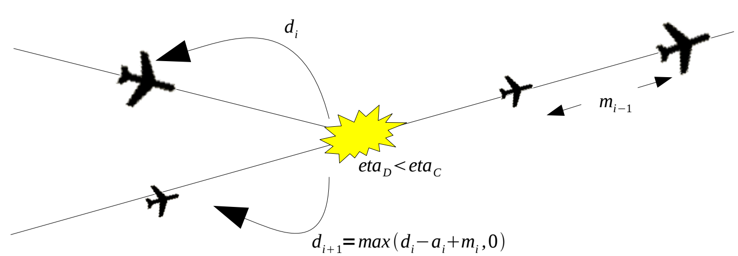

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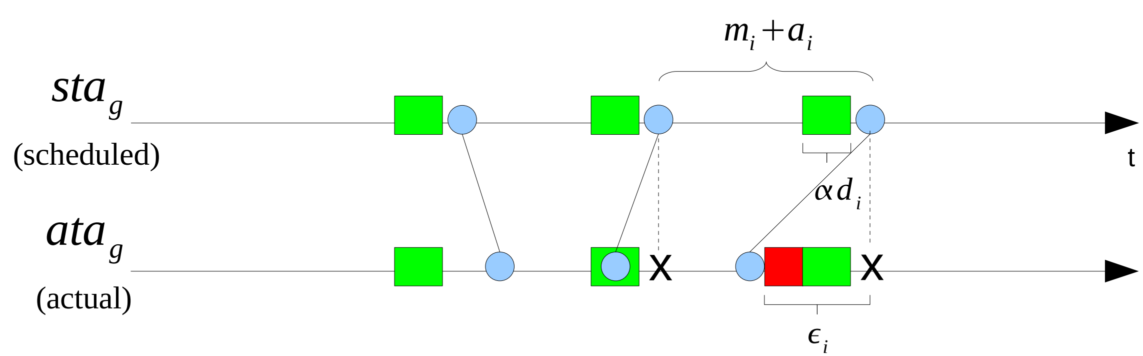

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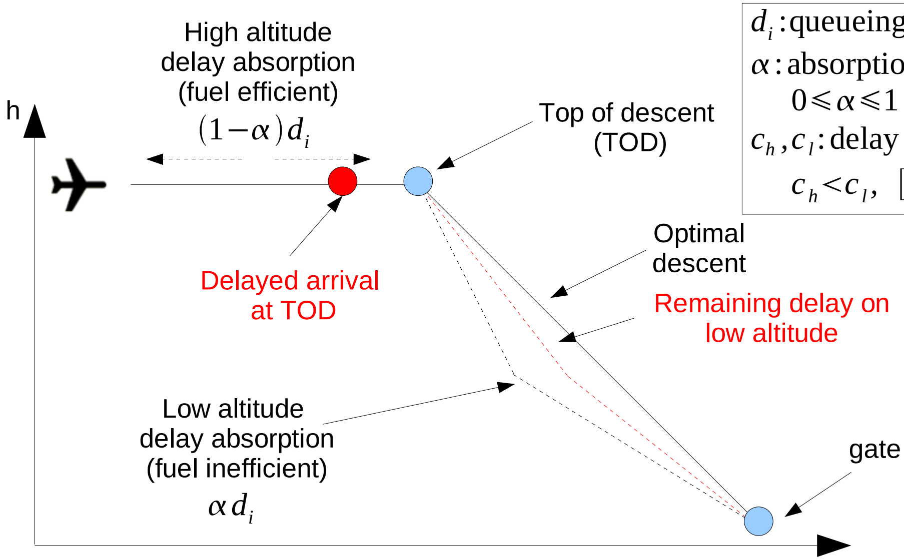

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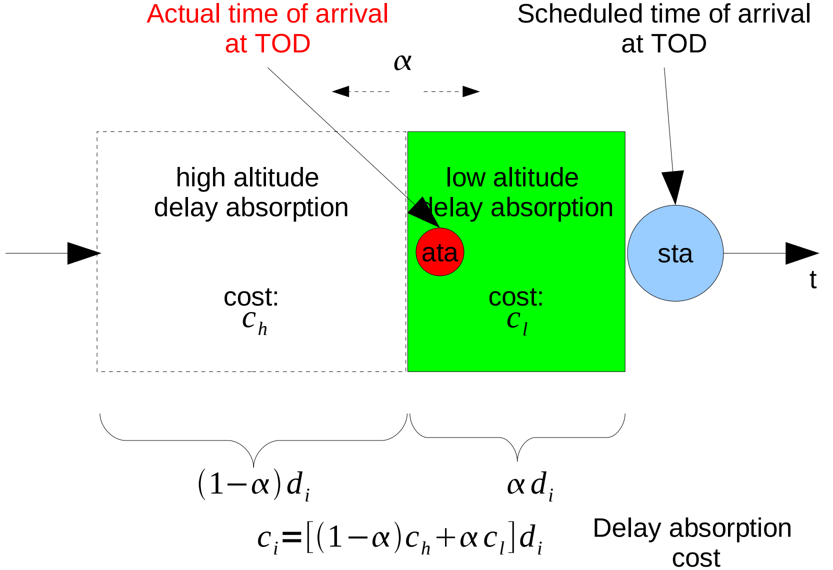

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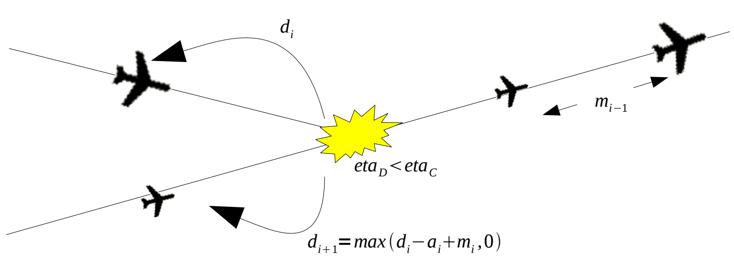

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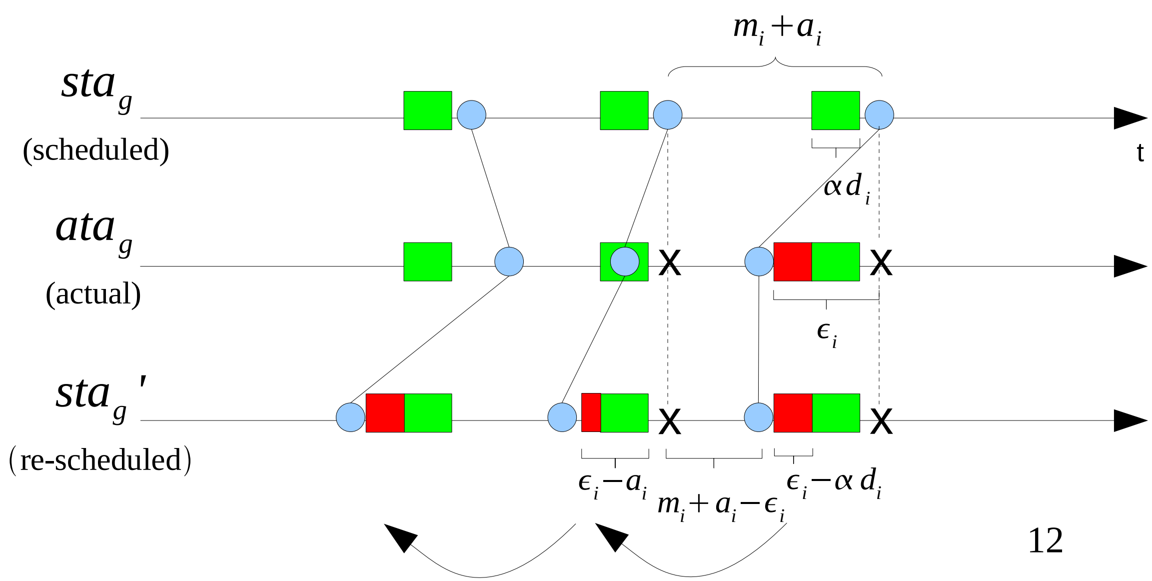

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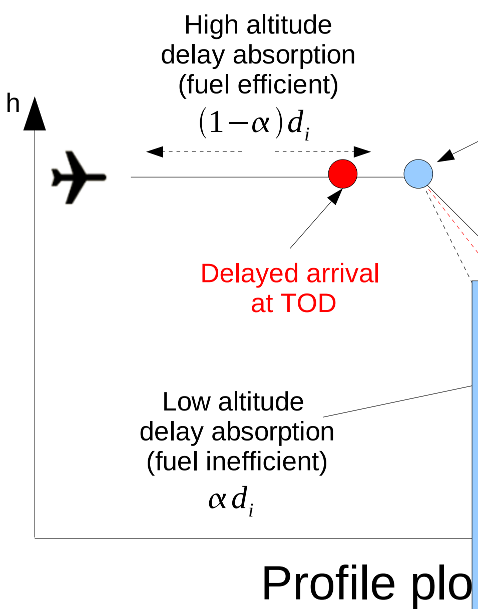
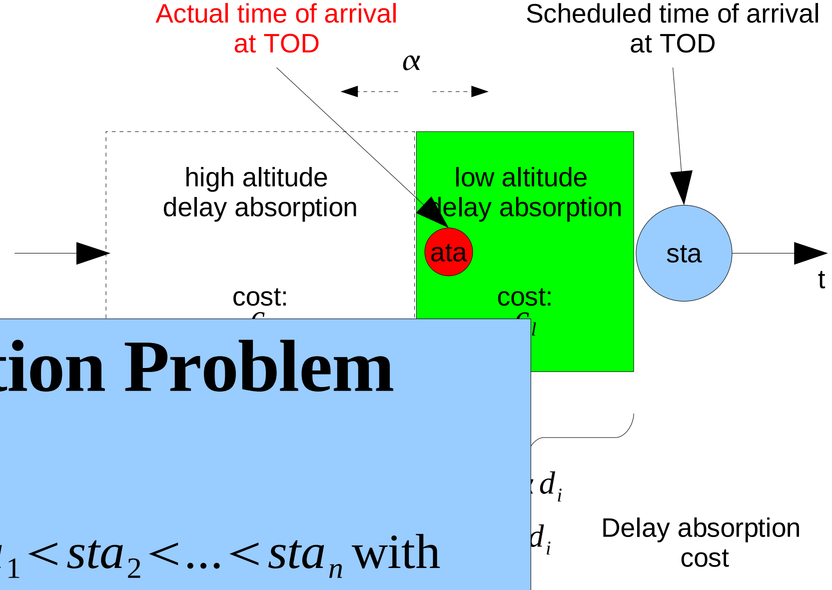




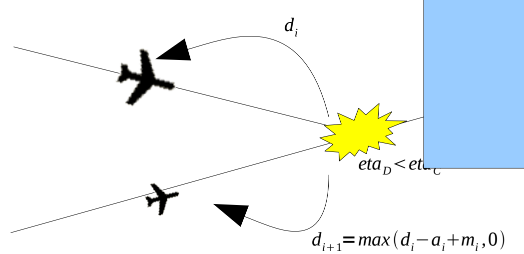
Traffic Synchronization Problem

Given :

Flow of pre-scheduled aircraft $sta_1 < sta_2 < \ldots < sta_n$ with queueing delays d_i and trajectory prediction errors ϵ_i.

Find :

Optimal delay absorption strategy.



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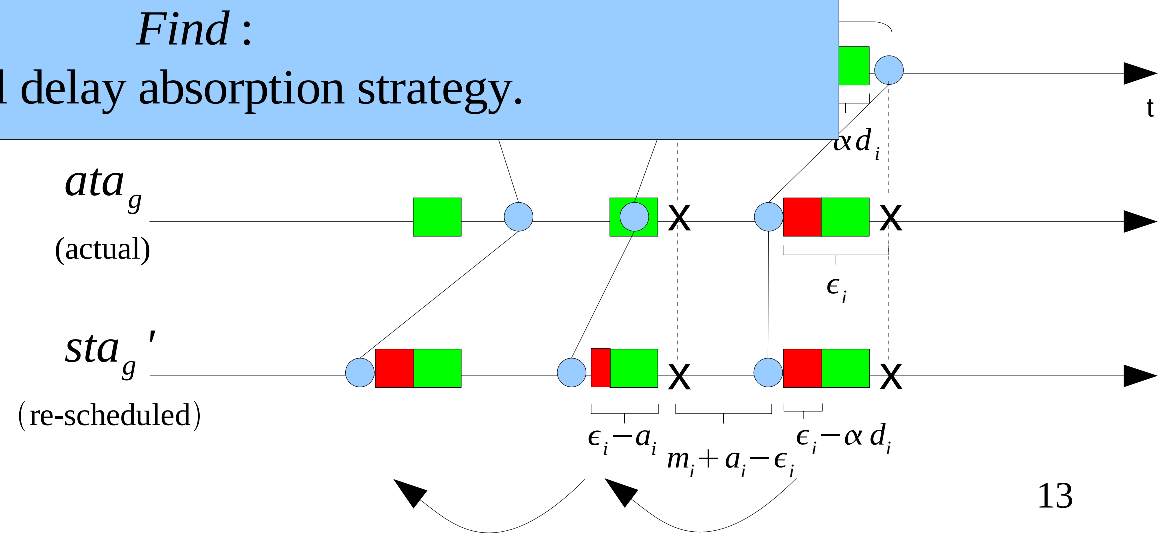
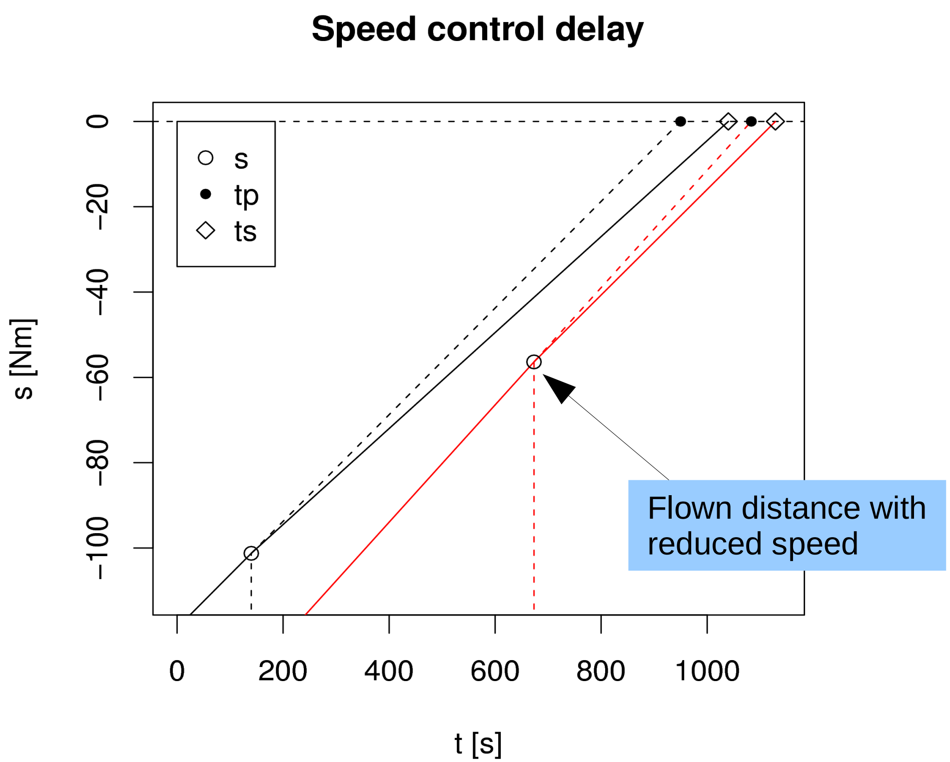
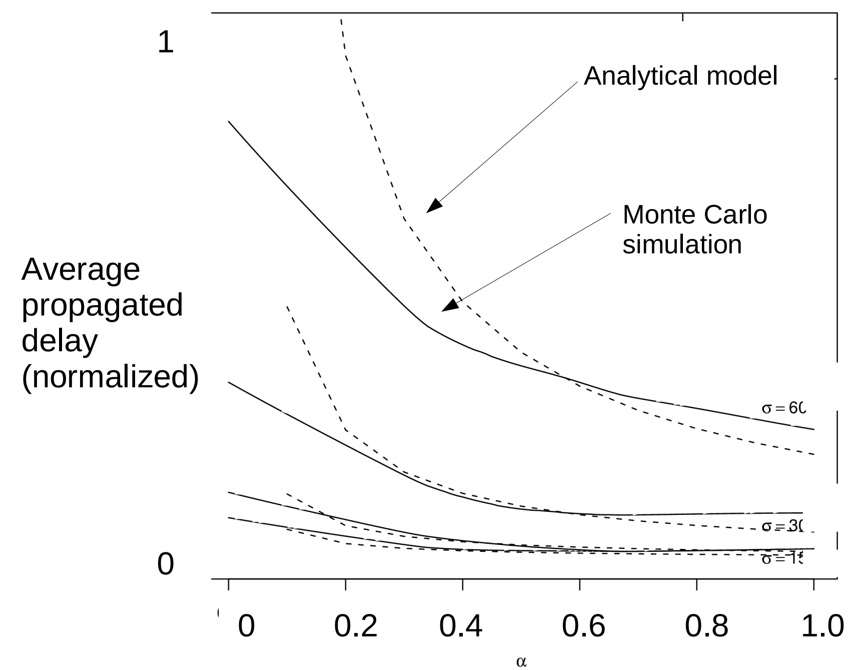


Delay propagation

[Erzberger 95, Bayen 06, Balakrishnan 09]

Main Results





$$\Delta_j \geqslant w_i - \frac{x_{j0} - l x_{i0}}{l v_i} + \frac{s_e}{k_i v_i}$$

with Δ_j: speed control delay for aircraft j

w_i: metering delay for aircraft i = j-1

$$\boldsymbol{E}(D_i) = \sum_{k=0}^{\infty} (k+1) \int_{u=0}^{\infty} \int_{v=0}^{u/\alpha} (u - \alpha v) P(k \mid u, v) f(u) g(v) \, dv \, du$$

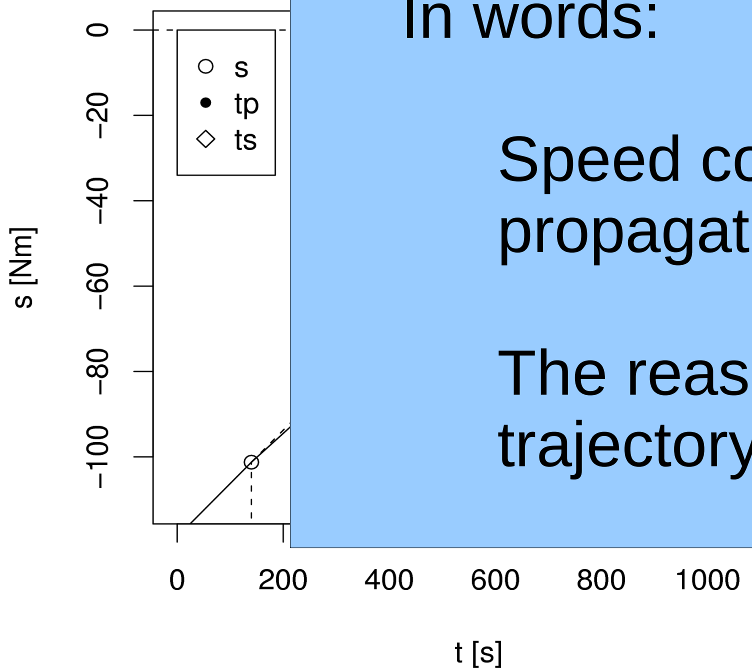
with

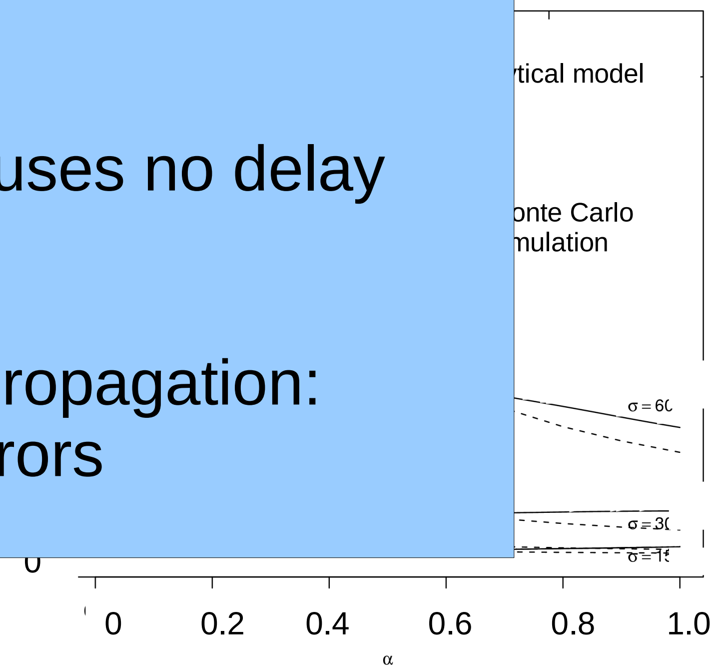
f, g: probability density function of ϵ, d

P: distribution of length of propagation

[Gwiggner et al. 09, 10]

Main Results





In words:

Speed control itself causes no delay propagation.

The reason for delay propagation: trajectory prediction errors

$$\Delta_j \geq w_i - \frac{x_{j0} - l x_{i0}}{l v_i} + \frac{s_e}{k_i v_i}$$

with Δ_j: speed control delay for aircraft j

w_i: metering delay for aircraft i = j-1

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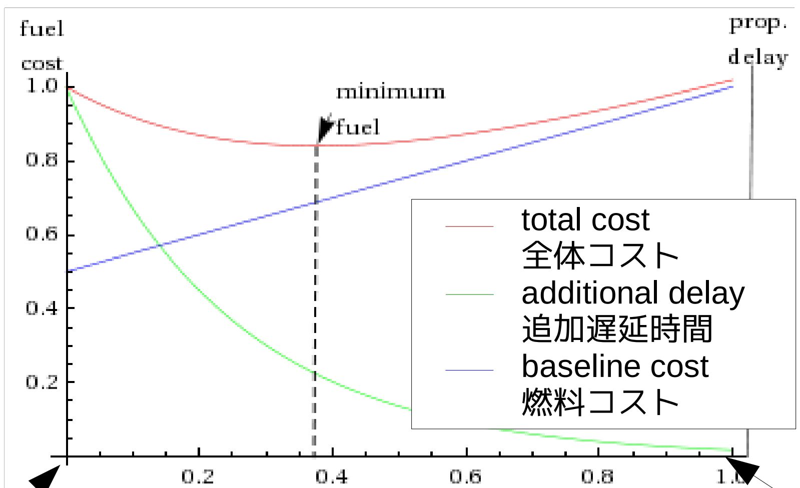
[Gwiggner et al. 09, 10]

Delay absorption strategy



High altitude only
高高度のみ

Fraction of metering delay absorbed in low altitude
低高度での滞留時間の割合

Low altitude only
低高度のみ

$$c(\alpha) = [c_L \alpha + c_H (1-\alpha)] d(\alpha)$$
$$d(\alpha) = d_0 + d_p(\alpha),$$

average delay + propagation

where

$c_L \gg c_H$: cost of delay absorbtion (kg/min)

d_0: average queueing delay

$d_p(\alpha)$: propagated delay

- Delay absorption strategy
  - Trade-off

High altitude
High propagated delay

Low altitude
High fuel consumption

  - Fuel efficiency
  - Workload sharing

Consequences:

- Even in the future, there is a need for radar vectoring.
- Sequencing strategies under uncertainties should be studied.

Conclusions

- Traffic Synchronization
  - Tactical management of queues of aircraft
- Delay Propagation
  - Delay propagation <u>due to</u> trajectory prediction errors
- Delay absorption strategy
  - Trade-off between high altitude (fuel efficient) and low altitude (fuel inefficient)
  - <u>Even when</u> the objective is to minimize fuel (!)

Future work

- Fundamental Research
  - Conditions for existence of minimum
  - Delay propagation in transportation networks
- Operational Concept
  - Ground delay vs. en-route delays
  - Delay management strategies

Thank you.

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Traffic Synchronization

Tactical phase

Global ATM Concept (ICAO)

Demand/Capacity Balancing
需要／容量均衡化

Traffic Synchronization
- Departure
- Arrival
- Interaction

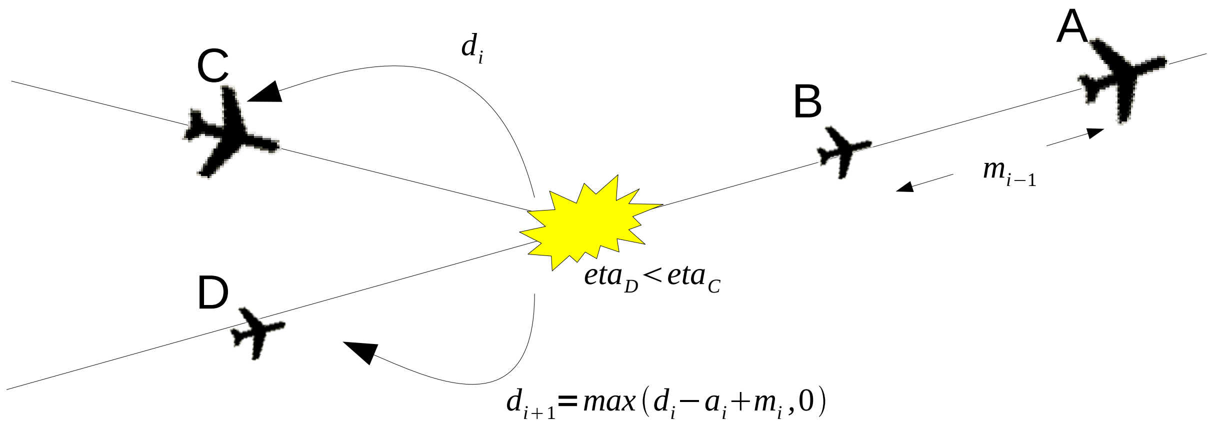
Conflict Management
コンフリクト管理

Traffic Management Coordinator (TMC)
航空交通管理管制官

Air Traffic Controller (ATCo)
航空管制官

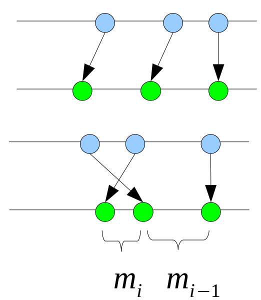
[ICAO 2005, ATM Masterplan]

Aircraft sequencing



Basic Operations

- Sequencing
  - *First-come-first-served (FCSF)*
  - *Constrained position shifting (CPS)*



- Metering
  - Flow control with separation constraints m_i

m_i	Follower	
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Heavy	90	120
Mid/Small	60	60

Queueing Delay

Aircraft	eta	sta	delay
A	12:01	12:01	0
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D	12:04	12:05	1
C	12:05	12:07	2

FCFS delay: 4 min
CPS delay: 3.2 min

[Erzberger 95, Bayen 06, Balakrishnan 09]

Delay propagation

<u>Condition for delay propagation:</u>

$$\epsilon_i \geqslant \alpha d_i$$

$$(\epsilon_i - a_i) \geqslant \alpha d_{i+1}$$

$$\dots$$

$$(\epsilon_i - a_i) - \sum_{j=1}^{k} a_{i+j} \geqslant \alpha d_{i+k+1} \qquad (1)$$

<u>Delay triggered by aircraft *i*:</u>

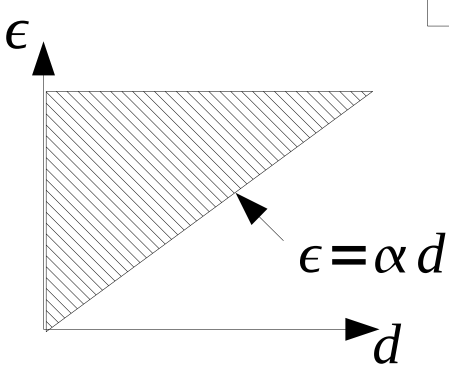
$$D_{p,i} = [k(\epsilon_i - a_i) - (k-1)a_{i+1} - \dots - a_{i+k}] - \alpha \sum_{j=0}^{k} d_{i+j+1} \qquad (2)$$

$$= k\epsilon_i - \underbrace{\sum_{j=0}^{k} (k-j) a_{i+j}}_{\approx 0} - \underbrace{\alpha \sum_{j=0}^{k} d_{i+j+1}}_{\approx k \alpha d_i} \qquad (3)$$

where k is smallest number, such that (1) is smaller than αd_k

<u>Propagation approximation (high-congestion):</u>

$$D_{p,i} \approx \begin{cases} (n-i)(\epsilon_i - \alpha d_i), & \epsilon_i \geqslant \alpha d_i \\ 0 & , \text{else} \end{cases} \qquad (4)$$



<u>Expectation:</u>

$$\boldsymbol{E}(D_{p,i}) = (n-i) \int_{u=0}^{\infty} \int_{v=0}^{u/\alpha} (u - \alpha v) f(u) g(v)\, dv\, du \qquad (5)$$

with

f, g: probability density function of ϵ, d