12 Air Traffic Control

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Recap

- Background
  - Static & dynamic routing
  - Applications
- Single & parallel queues
  - Arrival process & service processes
  - Single queue
  - Parallel queues
- Queuing networks
  - Model
  - Bernoulli routing
  - Dynamic routing

Outline

- Introduction to air traffic control
- Microscopic optimization
  - 4-dimensional trajectory
  - Practical considerations
  - Optimization
- Macroscopic optimization
  - Scheduling
  - Congestion pricing
- Summary

Introduction to Air Traffic Control

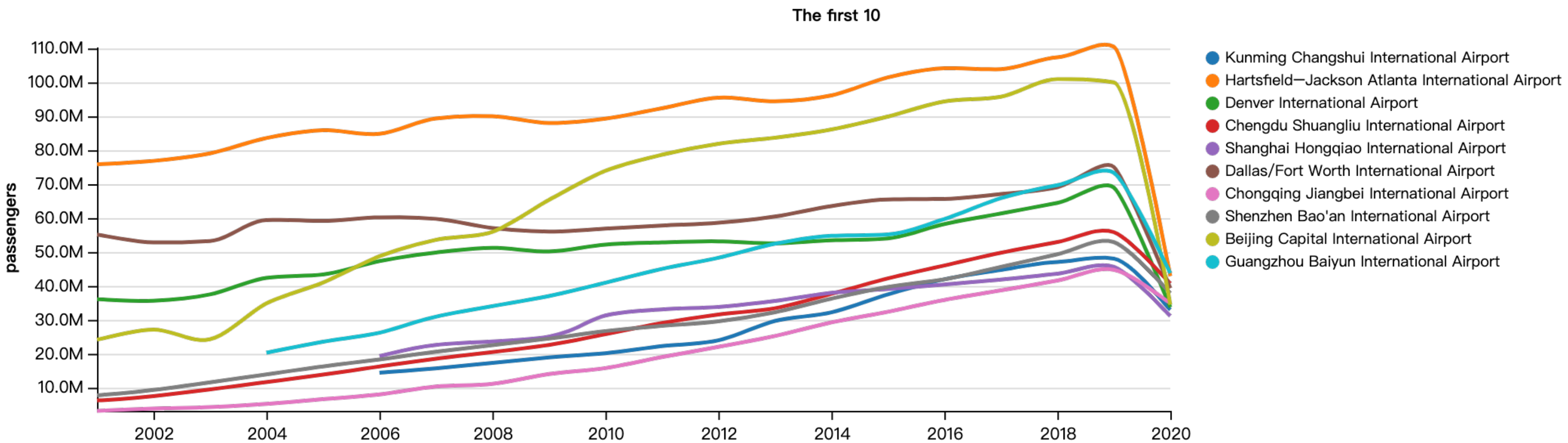
- https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-72-air-traffic-control-fall-2006/lecture-notes/lec1.pdf

Air transportation

Airspace is increasingly congested

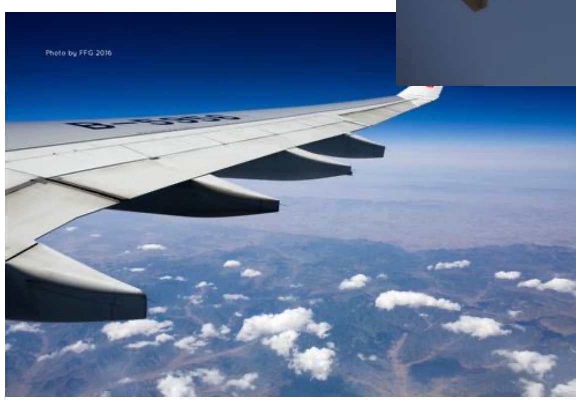
- Hartsfield-Jackson Atlanta International Airport
  - 879,560 aircraft movements (takeoff or landing) in 2017
  - More than 100 movements per hour
- Percentage of on-time flights (2019)
  - China: 77.60% (133.cn)
  - US: 78.66% (bts.gov)

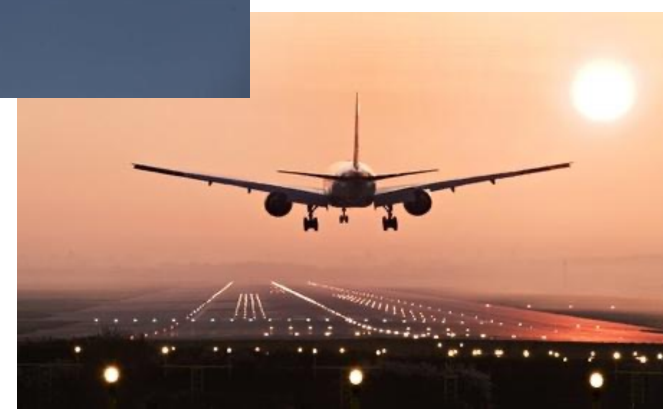
https://v.qq.com/x/page/j03950axod7.html



Phases of a flight

- Taxi
- Take off
- Climb
- Cruise
- Approach
- Descend
- Land
- Taxi





Air traffic control functions & infrastructure

Functions

- Aircraft separation assurance
- Traffic congestion management
- Flight information
- Search and rescue

Infrastructure

- Airports: runways, terminals, ground transport interface, servicing, maintenance
- Air traffic management: Communications, navigation, surveillance, control
- Weather: observation, forecasting, dissemination

Road traffic vs. air traffic

Road
- Highly distributed
- Primary cost: time
- Less sensitive to weather
- Low automation level

Air
- Highly centralized
- Primary cost: fuel
- Extremely sensitive to weather
- High automation level

Microscopic optimization

- Ground operations
- Terminal-area operations
- En-route operations

Formulation

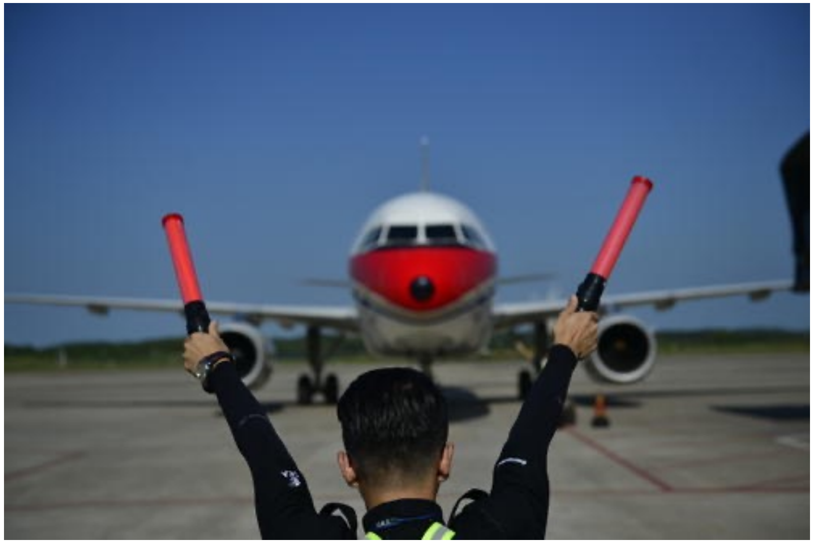
- Data
  - Flight path/itinerary
- Decision variables
  - 4D trajectories
- Constraints
  - Safety
  - Saturation
  - Operational
- Objective function
  - Minimize cost (fuel + time)

Scenarios

- Ground operations
  - Taxiing
  - Queuing for take-off
- Terminal-area operations
  - Approach, descent, landing
  - Take-off, climb

Ground operations

- Aircraft scheduled for departure & take-off
- Aircraft move from terminal to runway via taxiways
- As important as airborne movement (Tenerife 1977)
- Reference: Simaiakis, I., & Balakrishnan, H. (2009, August). Queuing models of airport departure processes for emissions reduction. In *AIAA Guidance, Navigation, and Control Conference* (p. 5650).

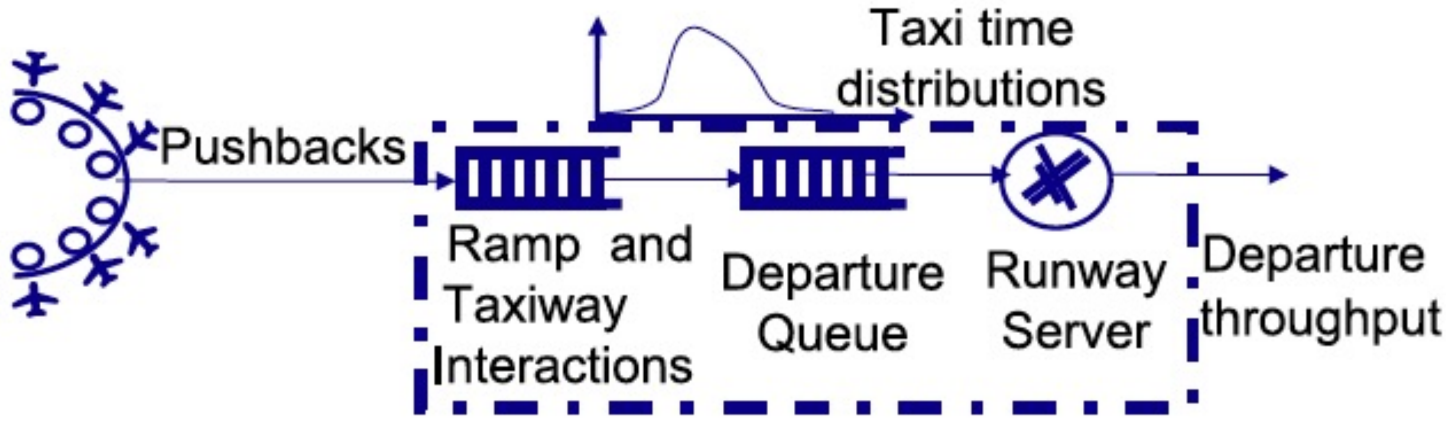


Queuing model for departure process

- Arrival process: controlled ("pushbacks")
- Service process: runway
- Total taxi-out time (i.e. from terminal to runway) is

t = nominal taxi-out time + taxiway delay + takeoff delay

- Idea of pushback control: having aircraft wait at terminal is much less costly than on taxiway



Terminal-area operations

- Consider a terminal area, i.e. the neighborhood if an airport.
- n aircraft will land at the airport.
- Time of arrival at the terminal area: $t_1, t_2, \ldots, t_n$
  - Jin, L., Cao, Y., & Sun, D. (2013). Investigation of potential fuel savings due to continuous-descent approach. *Journal of aircraft*, *50*(3), 807-816.

3-dimensional trajectory

- Initial conditions
  - $x_i(t_i) \in \mathbb{R}^3$ (longitude, latitude, altitude)
  - $v_i(t_i) \in \mathbb{R}^3$ (longitudinal speed, latitudinal speed, vertical speed)
- Terminal conditions (T_i = landing time)
  - $x_i(T_i) = 0$ (location of airport)
  - $v_i(T_i) \in V_{landing}$ (landing configuration)
- Intermediate trajectory
  - $x_i(t), t = t_i, t_i + 1, \ldots, T$
  - $v_i(t), t = t_i, t_i + 1, \ldots, T$

Cost function*

- Dynamic equation

$$(\mathrm{Thr} - D)V_{\mathrm{TAS}} = mg_0\dot{h} + mV_{\mathrm{TAS}}\dot{V}_{\mathrm{TAS}}$$

Thr	thrust's projection along the velocity vector
D	aerodynamic drag
m	aircraft mass
h	geodetic altitude
$g0$	gravitational acceleration
V_{TAS}	true airspeed

Cost function*

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Cost function*

- Air drag

$$D = \frac{C_{D0}\rho S}{2}v^2 + \frac{2C_{D2}m^2 g_0^2}{\rho S}\frac{1}{v^2}$$

- C_{D0} and C_{D2} are coefficients associated with the drag coefficient that are dependent of the flap setting, ρ is air density, and S is the wing reference area.
- Thrust specific fuel consumption (TSFC)

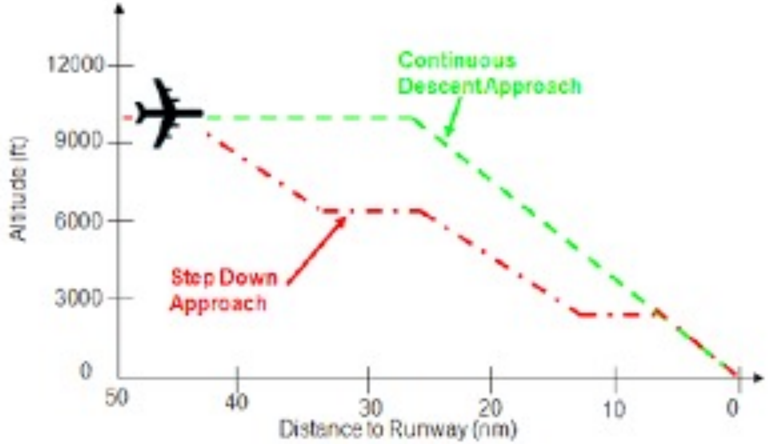
$$\eta = C_{f1}\left(1 + \frac{v}{C_{f2}}\right)$$

- Fuel flow rate

$$\mathrm{fr} = C_f \mathrm{Thr} \cdot \eta$$

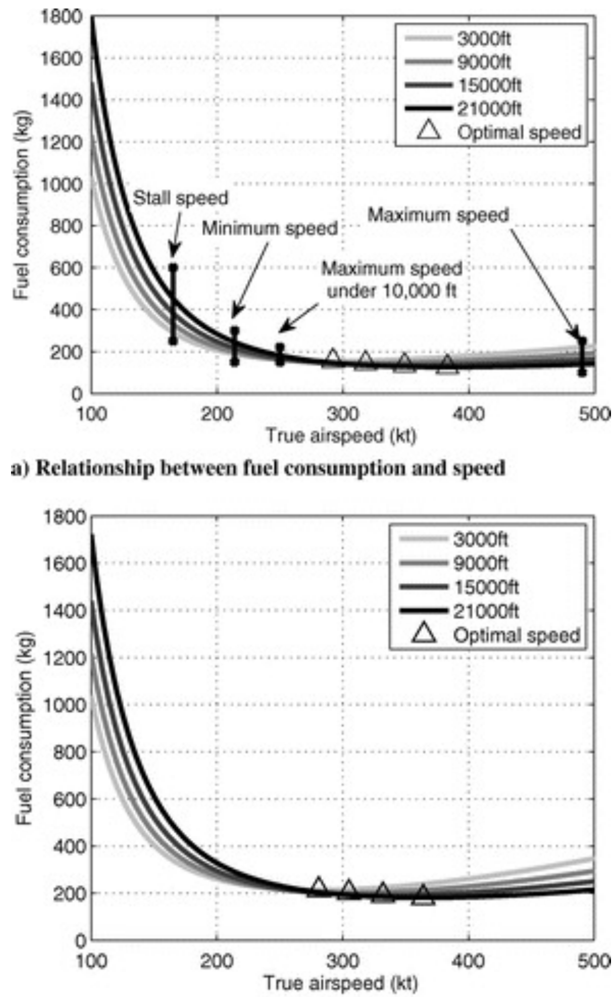
Continuous descent*

- Direct optimization of the trajectories is extremely involved due to
  - Nonlinear constraints
  - Very complex cost function
- Instead, we can analyze properties of the cost function and propose solutions expected to perform well
- One such solution is so-called continuous descent approach (CDA)



Speed optimization

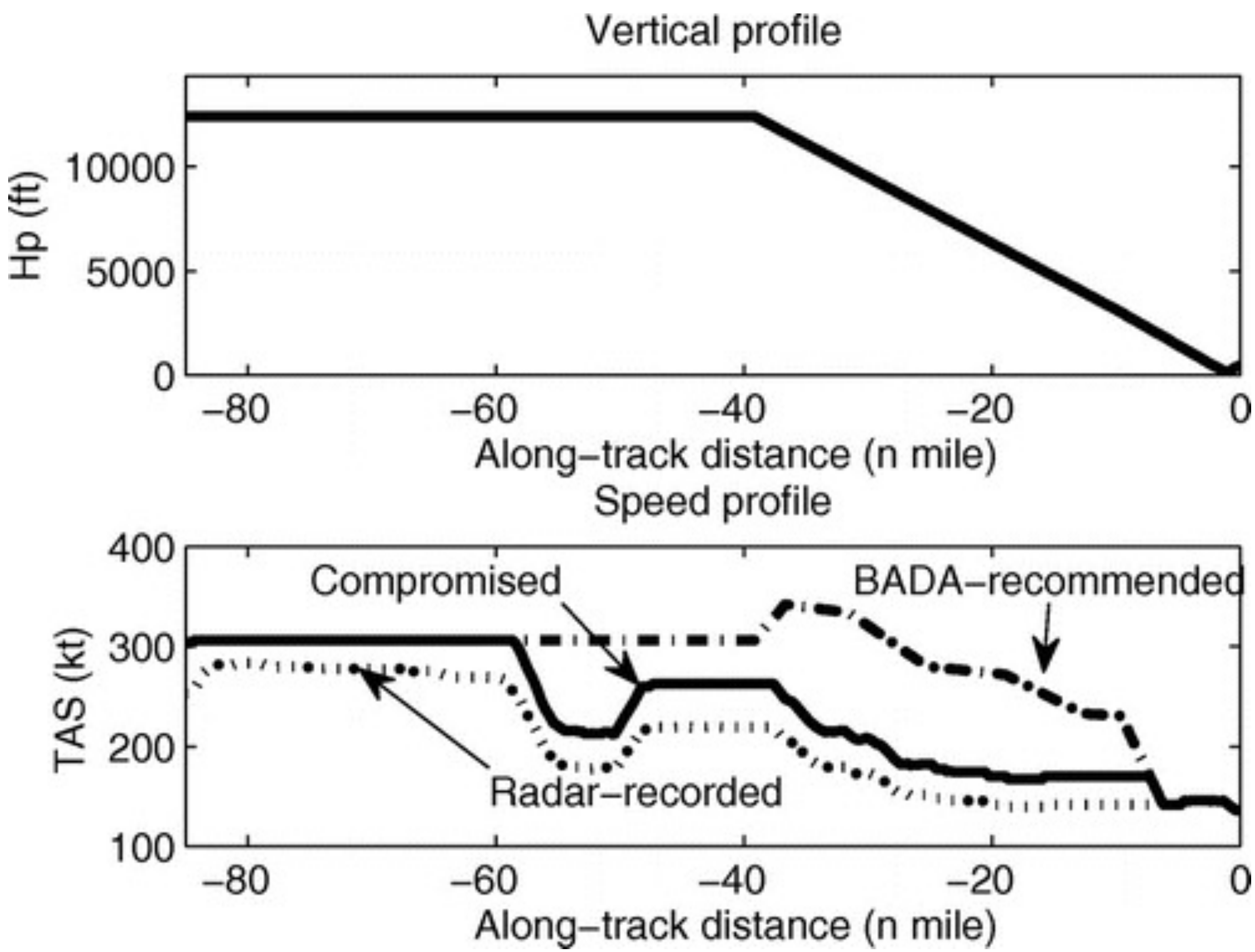
- We first determine the fuel-optimal speed
- Aircraft need airspeed to stay in the air
- Speed too low: to avoid stall, engines must provide very high thrust -> inefficient
- Speed too high: air drag increases. Also, aircraft structure cannot withstand excessively high speed



a) Relationship between fuel consumption and speed

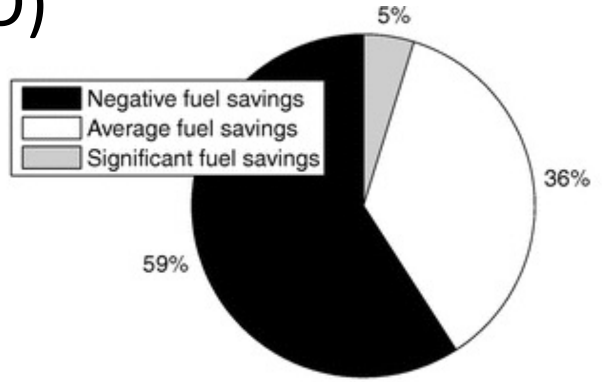
b) Fuel curves given by the Volpe model [14]

Replacing level-off with CDA

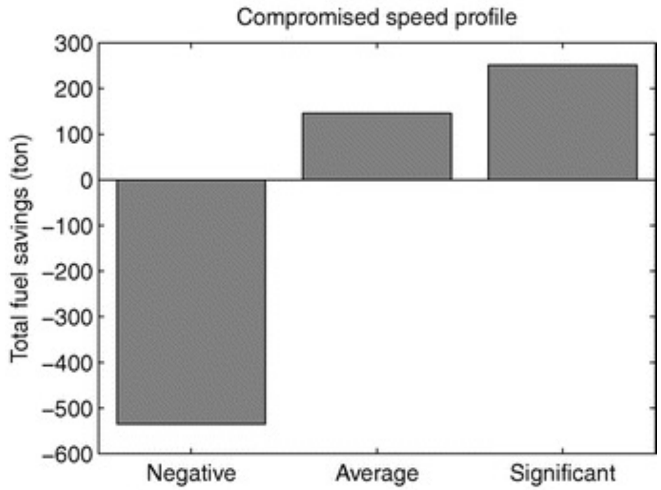


Simulation results

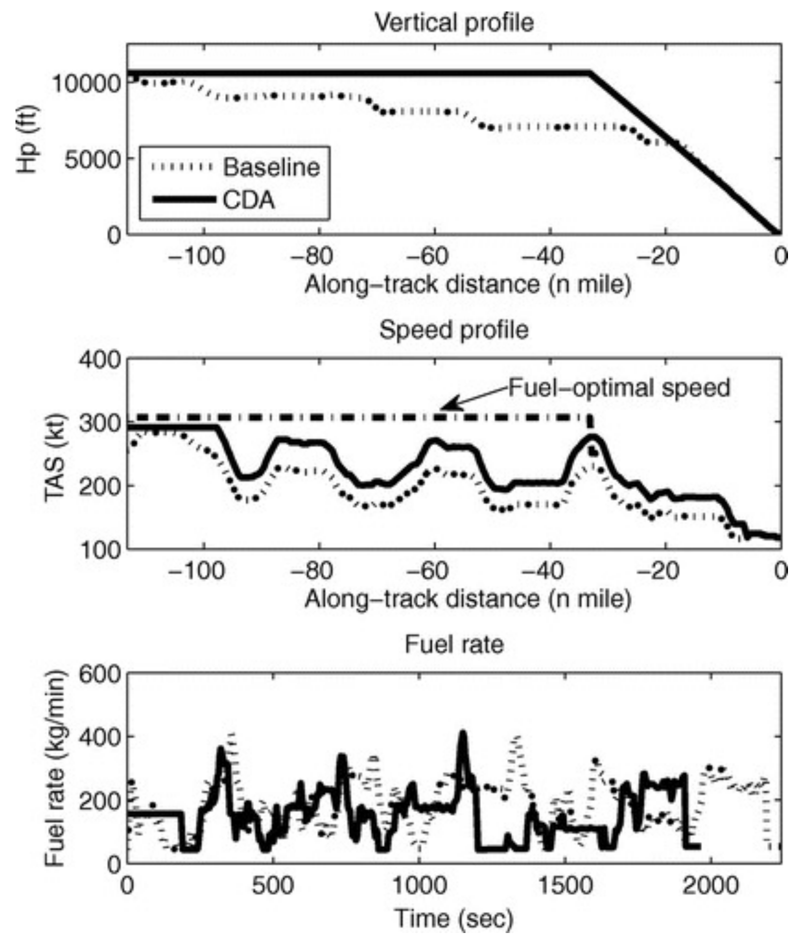
- One-day traffic at San Francisco International Airport (SFO)



a) Total distribution



b) Amount of saved fuel



Macroscopic optimization

- Traffic flow management
- Landing sequencing

En-route optimization

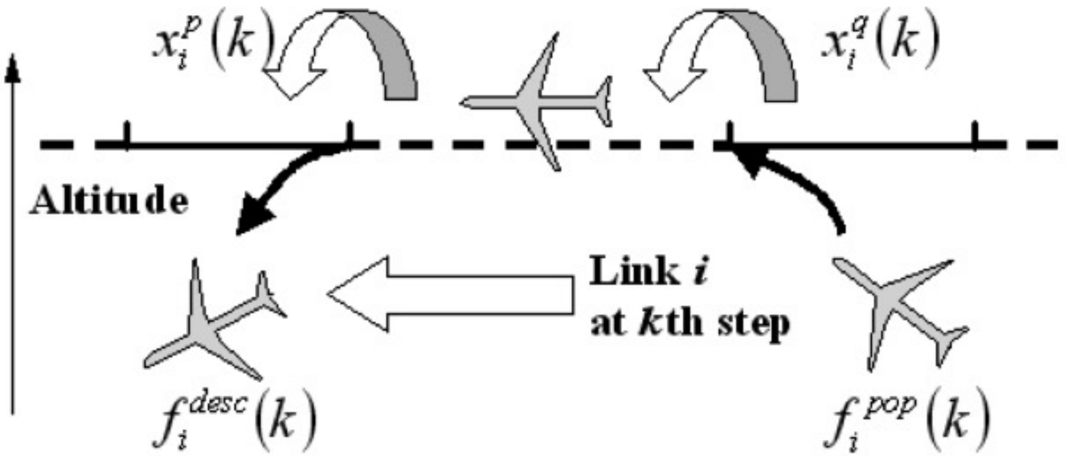
- Cell transmission model (aggregate)
- Similar to road traffic, with technical differences
- On-ramp -> climb, off-ramp -> descent
- Sun, D., & Bayen, A. M. (2008). Multicommodity Eulerian-Lagrangian large-capacity cell transmission model for en route traffic. *Journal of guidance, control, and dynamics*, *31*(3), 616-628.

En-route optimization

Model formulation

- A network of links indexed by 1,2,...,N
- Link i contains m_i cells, each cell has $x_i^1(k)$, $x_i^2(k)$, … , $x_i^{m_i}(k)$ aircraft at time k
- Forcing input $f_i^{in}(k)$: # of aircraft entering link i at time k
- Descent input $f_i^{desc}(k)$: # of aircraft leaving link i and descending to a lower flight level
- Climb input $f_i^{climb}(k)$: # of aircraft entering link i from a lower flight level

En-route optimization



- Control input $u_i(k)$: # of aircraft being held (delayed)
- Dynamic equation:

$$x_i(k+1) = A_i x_i(k) + B_i^f f_i(k) + B_i^u u_i(k)$$

- Safety constraint: $x_i^q(k)$ cannot exceed some threshold

Landing sequencing

- Single runway, mixed operations (takeoff & landing)
- Assume Bernoulli arrivals
- Half are small, half are large aircraft
- Small aircraft: fast takeoff/landing, less value of time (fuel)
- Prioritize small or large?
- Depends on both operation time and fuel rate.

Landing sequencing

- Having a large aircraft delay 1 min is much more costly than with a small aircraft -> put large in front of small
- However, such sequence (large followed by small) requires a larger headway between aircraft, compared with small followed by large
- A tradeoff is needed
- How to convince aircraft to accept assigned delay?
  - Pay the losers or charge the winners (congestion pricing)
  - Agreement with fleet operators
- Political issues may arise

Summary questions

- What are some similarities and differences between road and air transportation?
- What are aircraft trajectory optimization more challenging than CAV trajectory optimization?

Next time

- Smart grids