Integrated assessment modelling for aviation

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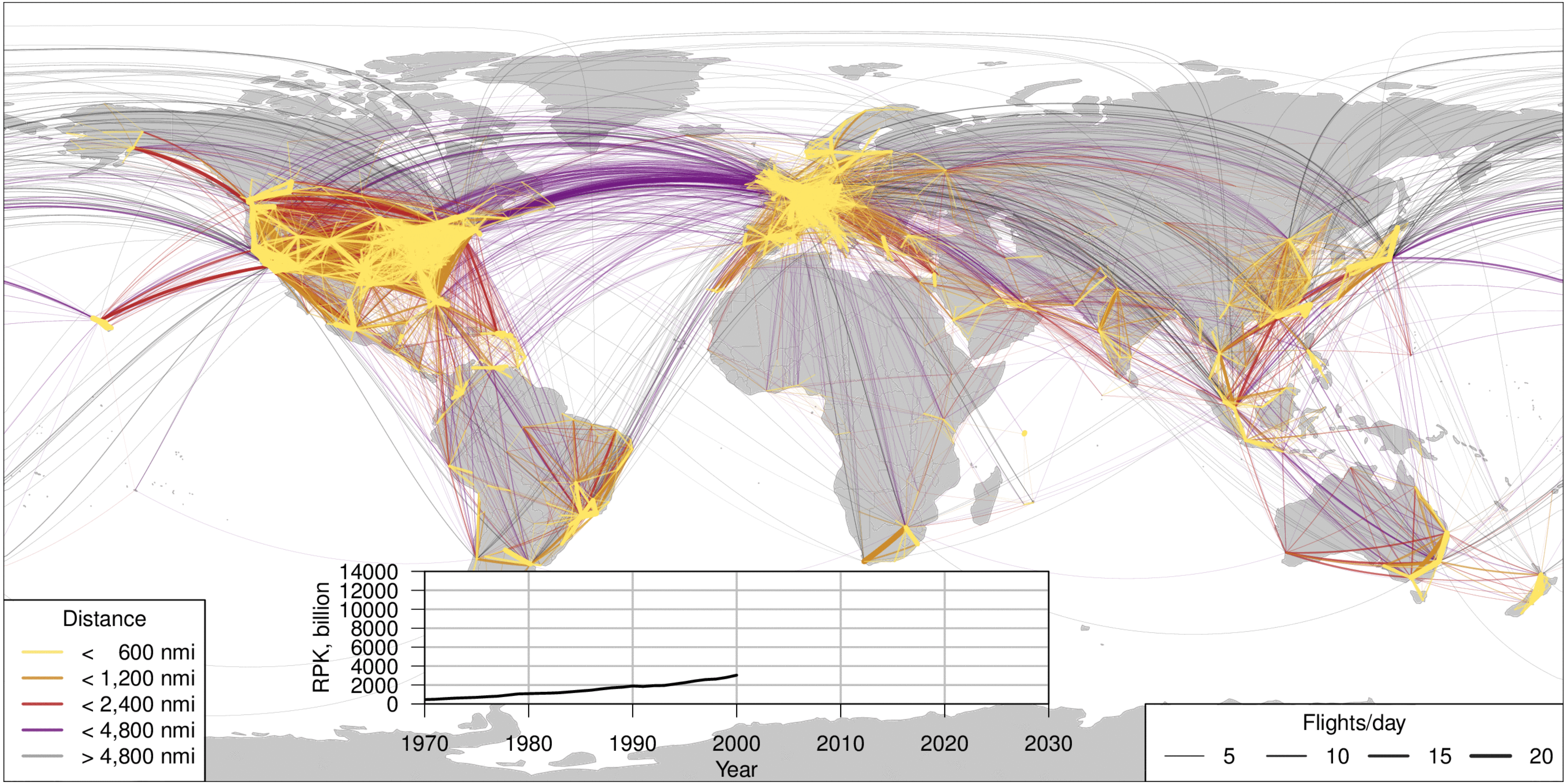
Background

- Aviation policy outcomes depend on the interaction of multiple stakeholders across different geographic scopes
    - Airlines, airports, ATC, passengers, regulators, manufacturers...
    - Complex relationships between capacity, scheduling, fleet, passenger demand, technology, networks etc.
- Answers to many questions affected by these interactions, e.g.
    - How does the system respond to emissions-mitigation policy?
        - CCC’s Net Zero report projects aviation as single highest-emitting UK sector in 2050 (CCC, 2019)
    - What are the wider impacts of capacity expansion?
        - Current total value of airport construction/expansion projects globally is > $600 billion (CIC, 2016)
    - Should we invest in battery electric aircraft as a feasible alternative to current technology?

➡ Airport Capacity Consequences Leveraging Aviation Integrated Modelling (ACCLAIM)

- Three year EPSRC-funded project between UCL, the University of Southampton and Imperial College
- Builds on the existing AIM model (University of Cambridge)



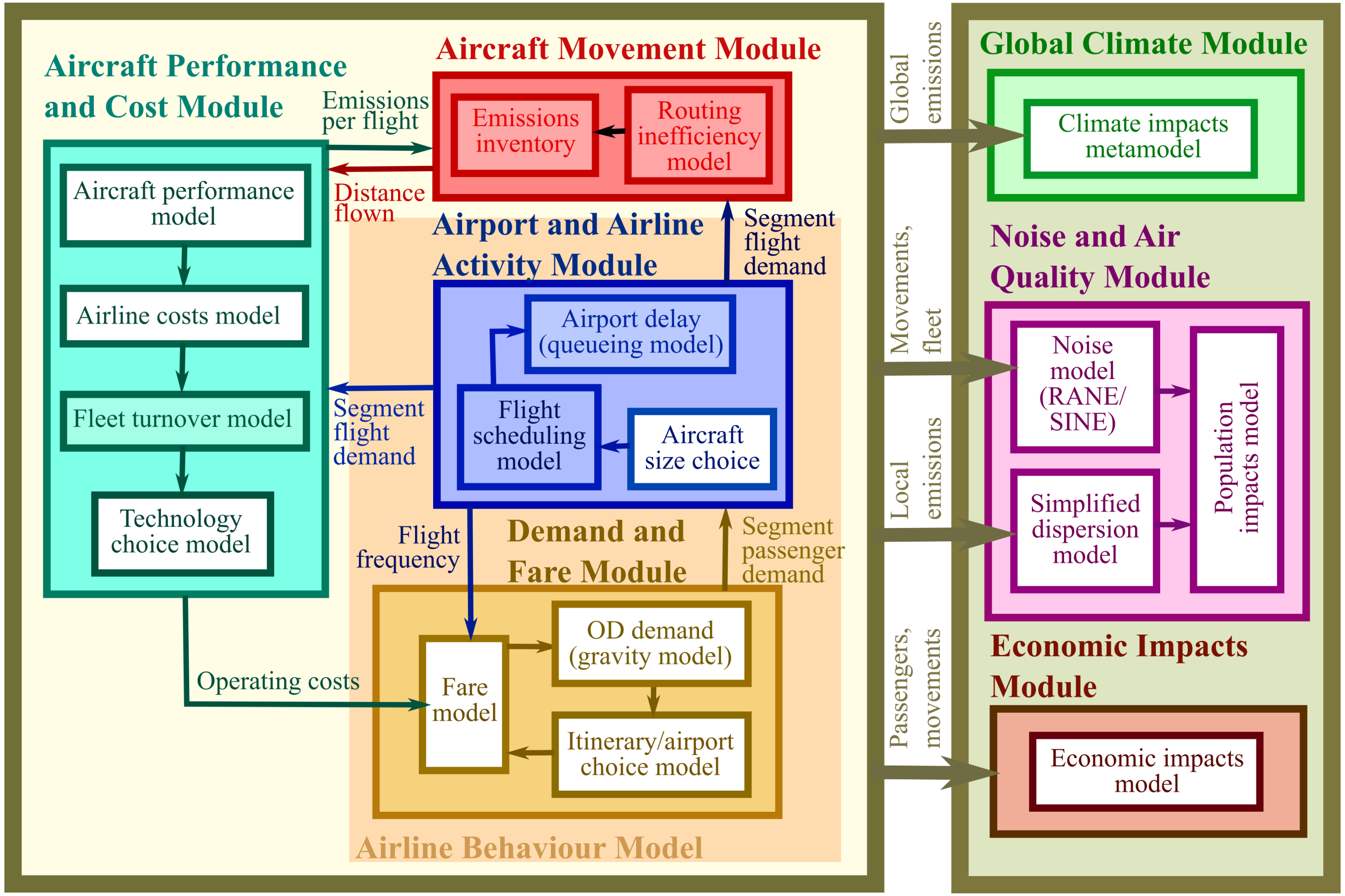
[Data: Sabre, 2017; ICAO, 2018]

How do we model the global aviation system?

Solve iteratively (AIM2015)

OR

Optimise profit per airline (Airline Behaviour Model)



Aircraft Performance and Cost Module

Aircraft performance model

Airline costs model

Fleet turnover model

Technology choice model

Emissions per flight

Distance flown

Segment flight demand

Operating costs

Aircraft Movement Module

Emissions inventory

Routing inefficiency model

Airport and Airline Activity Module

Airport delay (queueing model)

Flight scheduling model

Aircraft size choice

Segment flight demand

Flight frequency

Demand and Fare Module

Segment passenger demand

Fare model

OD demand (gravity model)

Itinerary/airport choice model

Airline Behaviour Model

Global emissions

Movements, fleet

Local emissions

Passengers, movements

Global Climate Module

Climate impacts metamodel

Noise and Air Quality Module

Noise model (RANE/ SINE)

Simplified dispersion model

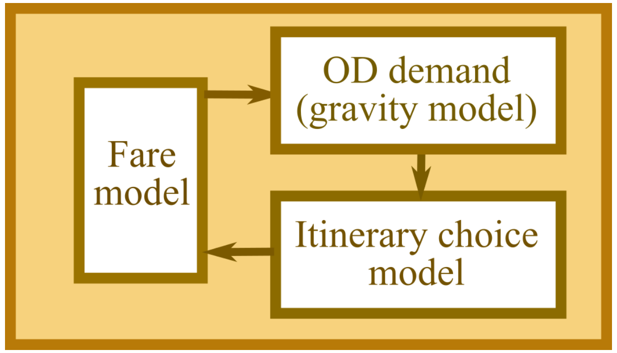
Population impacts model

Economic Impacts Module

Economic impacts model

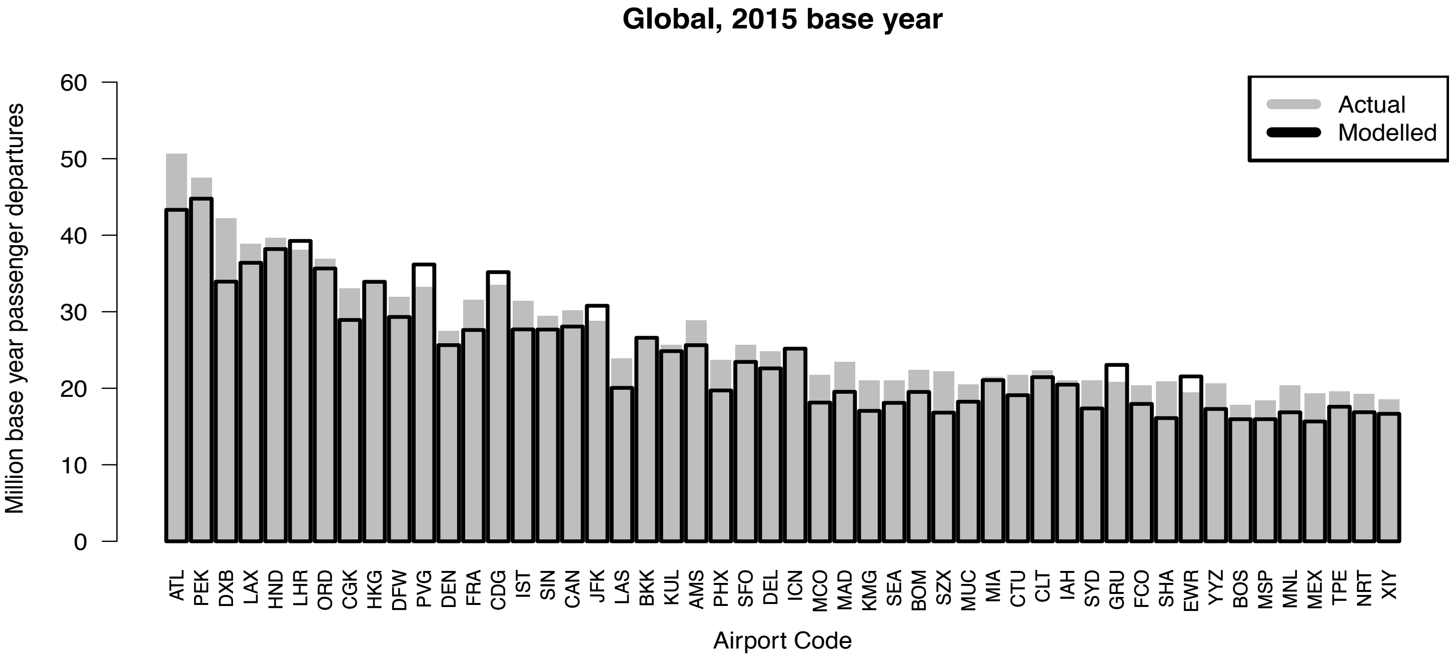
Open source – see www.atslab.org for more information/papers

Methodology – demand and fare module

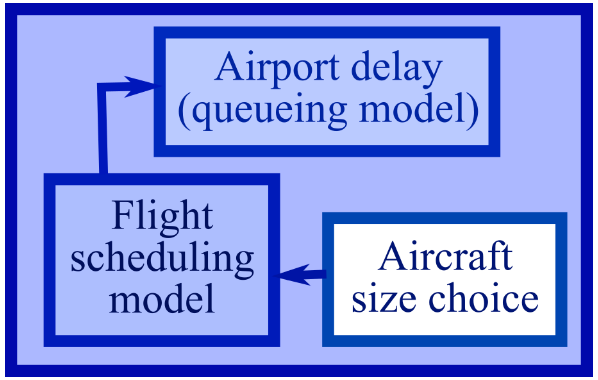


- Total city-city passenger **demand** depends on population, income, fare and other journey characteristics
- Gravity-type model estimated from Sabre (2016) data
- **Fare** depends on airline costs, competition, etc.

- Itinerary-level fare model estimated from global fare data (Wang et al. 2018)
- **Itinerary choice** depends on fare, frequency, number of flight legs, time etc.
- Estimated using a logit model


Global, 2015 base year

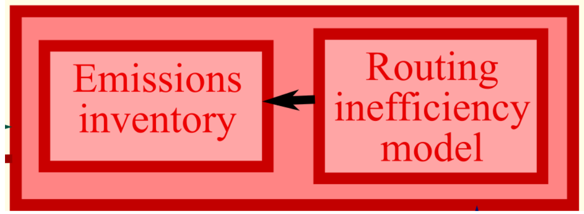
Methodology – airport and airline activity module



- Aircraft size choice model picks fleet to use based on demand, airport characteristics, etc.
  - ❑ Assuming typical segment load factors this gives flight frequency and fleet requirement
- Scheduling throughout the day is based on existing airport-level schedule structure
- Rapid queueing model for airport delay
  - Depends on demand for flights vs. airport capacity
  - Can also be used to project capacity required for delay to remain at current levels
  - See Evans (2008)

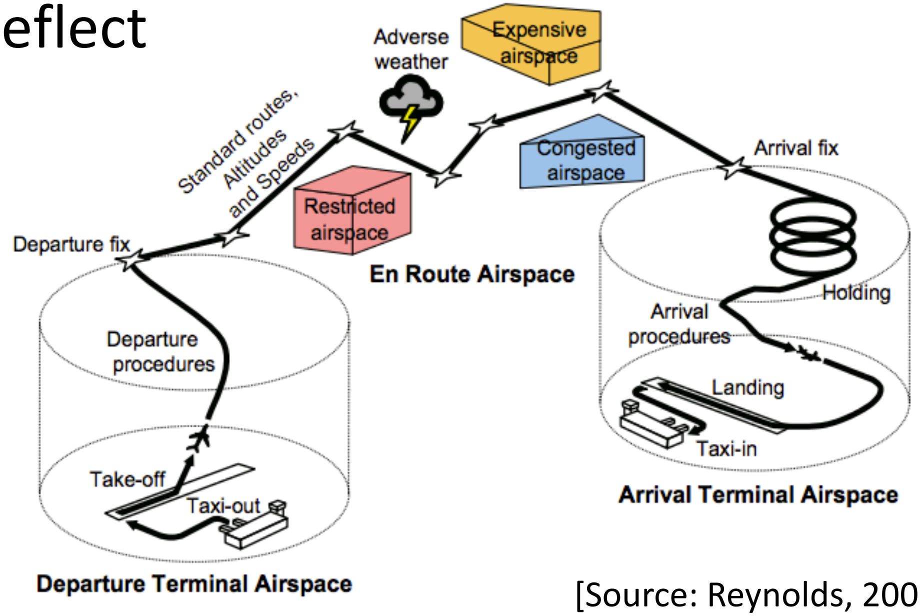
[Image: Mumbai Airport, Wikimedia commons]

Methodology – aircraft movement module


Emissions inventory
Routing inefficiency model

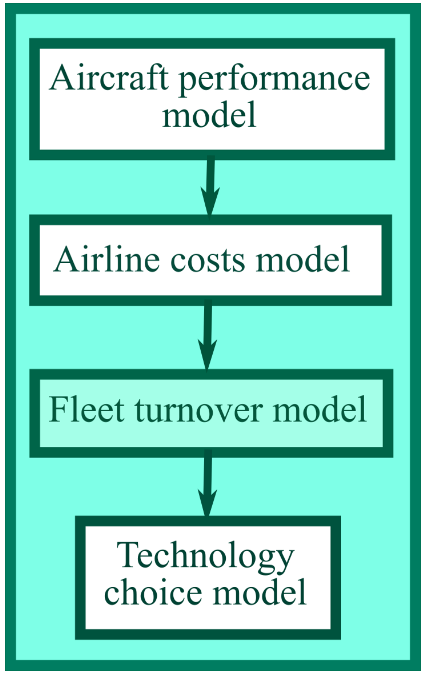
- Projects how fuel use/distance flown vary due to en-route inefficiencies (Reynolds 2008)
- Two components:
  - ❑ Ground track extension (derived from radar track data)
  - ❑ Impact of non-lateral inefficiencies (e.g. non-optimal speed or altitude) on fuel use
- Fuel use along great circle tracks is then adjusted to reflect this

Region	Average route length in data (nm)	Average TGTE (nm)	Average TGTE (%)	Flight data source
Intra Europe	415	57	14	FDR (n=4420)
Intra US	635	76	12	ETMS (n=2946)
Intra Africa	489	41	8	Mozaic (n=525)
North Atlantic	3430	176	5	Mozaic (n=3311)
Europe – Asia (typical)	4705	316	7	Mozaic (n=2448)
Europe-Asia (Extreme)	4730	1100	23	Mozaic (n=37)



[Source: Reynolds, 2008]

Methodology – aircraft performance and cost module



Aircraft performance model

Airline costs model

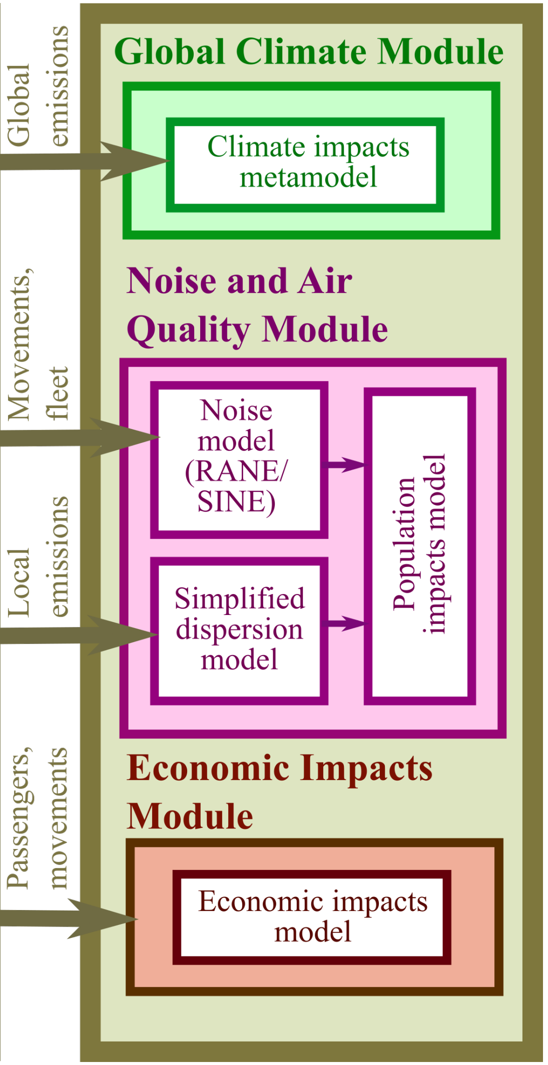
Fleet turnover model

Technology choice model

- Al Zayat et al. (2017) - performance and cost model development
  - Estimated performance model based on output from Piano-x for nine aircraft size classes
  - Operating costs by category based on ICAO and US Form 41 data
- Fuel use adjusted to reflect fleet composition and turnover (Dray 2013)
- NPV model for choice of new technologies (e.g. Dray et al. 2018)
  - E.g. future generation 'conventional' design + biofuel vs. battery electric narrowbody

Size Category	Approx. seat range	Reference aircraft	Reference engine
Small regional jet	30-69	CRJ 700	GE CF34 8C5B1
Large regional jet	70-109	Embraer 190	GE CF34 10E6
Small narrowbody	110-129	Airbus A319	V.2522
Medium narrowbody	130-159	Airbus A320	CFM56-5B4
Large narrowbody	160-199	Boeing 737-800	CFM56-7B27
Small twin aisle	200-249	Boeing 787-800	GEnx-1B67
Medium twin aisle	259-299	Airbus A330-300	Trent 772B
Large twin aisle	300-399	Boeing 777-300ER	PW4090
Very large aircraft	400+	Airbus A380-800	EA GP7270

Methodology – impact assessment modules



Global emissions
Movements, fleet
Local emissions
Passengers, movements

Global Climate Module

Climate impacts metamodel

Noise and Air Quality Module

Noise model (RANE/ SINE)

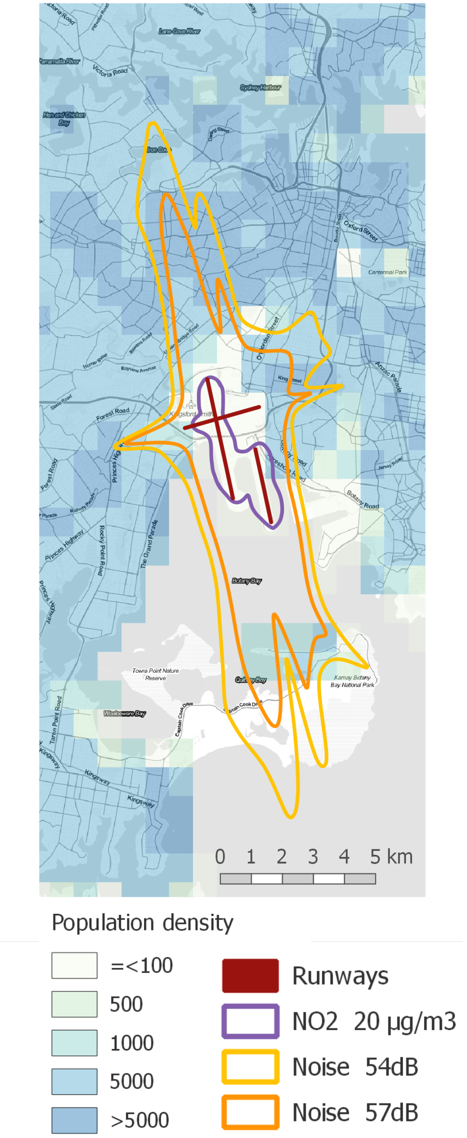
Simplified dispersion model

Population impacts model

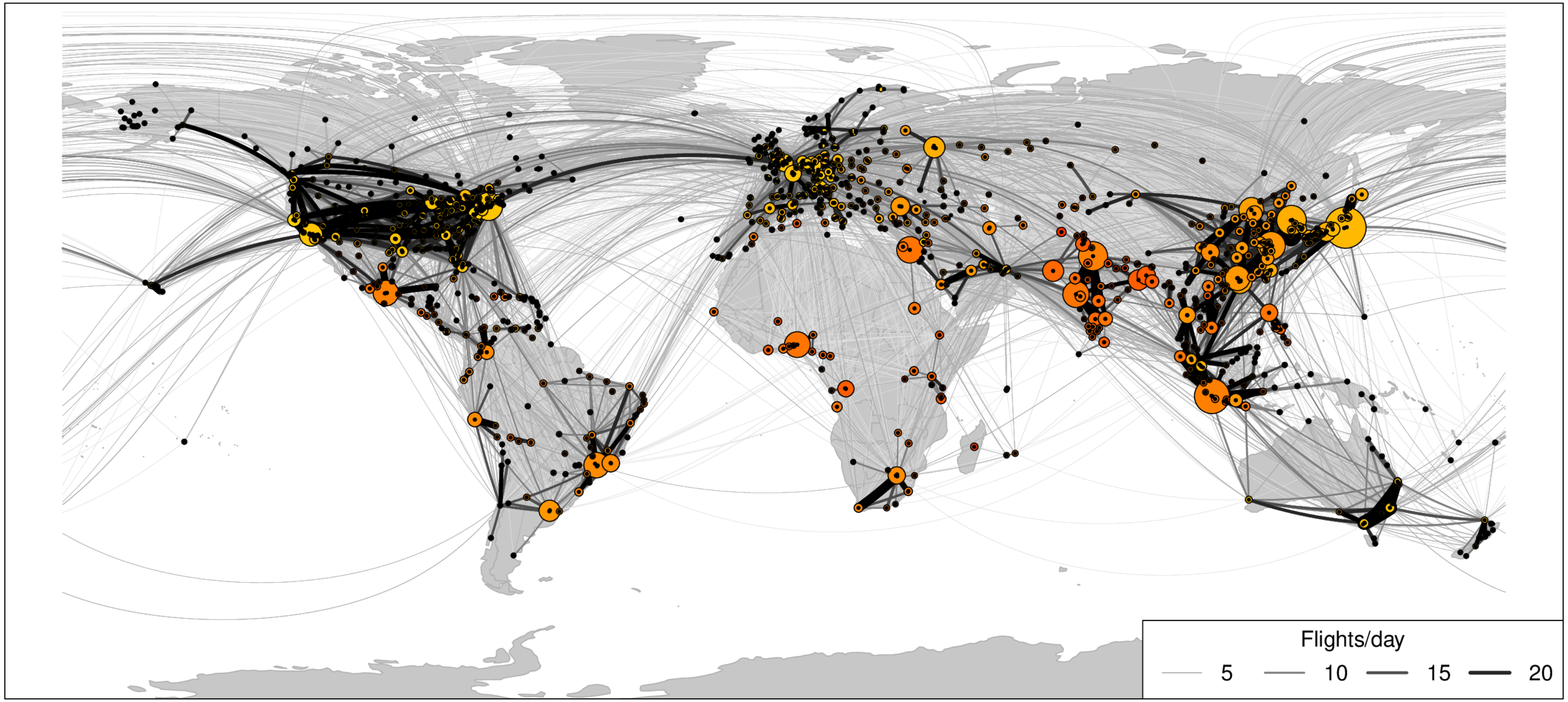
Economic Impacts Module

Economic impacts model

- These are simplified models intended to capture broad impacts on externalities
  - Climate modelling uses a metamodel based on p-TOMCAT output to get GWP/GTP
    - See e.g. Krammer et al. (2013)
  - Single-metric noise model (SINE) developed by Southampton University (Torija et al. 2016)
  - NOx estimates are generated by the performance model
    - For NO_2 we use Wood et al. (2008)
  - PM2.5 estimates use the FOX method (Stettler et al. 2013)
    - Note that all pollutant estimates are aircraft engine primary emissions only
  - Dispersion modelling uses RDC code (e.g. Barrett & Britter, 2009)
  - Economic impacts metamodel for employment/GVA
    - still in validation process



Modelling scope



- Flights between 1169 airports in 878 cities modelled
- 2015 base year
- Includes uncertainty
  - Lens approach for technologies
  - Plus a range of input scenarios

- Future projections to 2050 and beyond
  - Given projections of population, GDP/capita, oil price, technology etc.

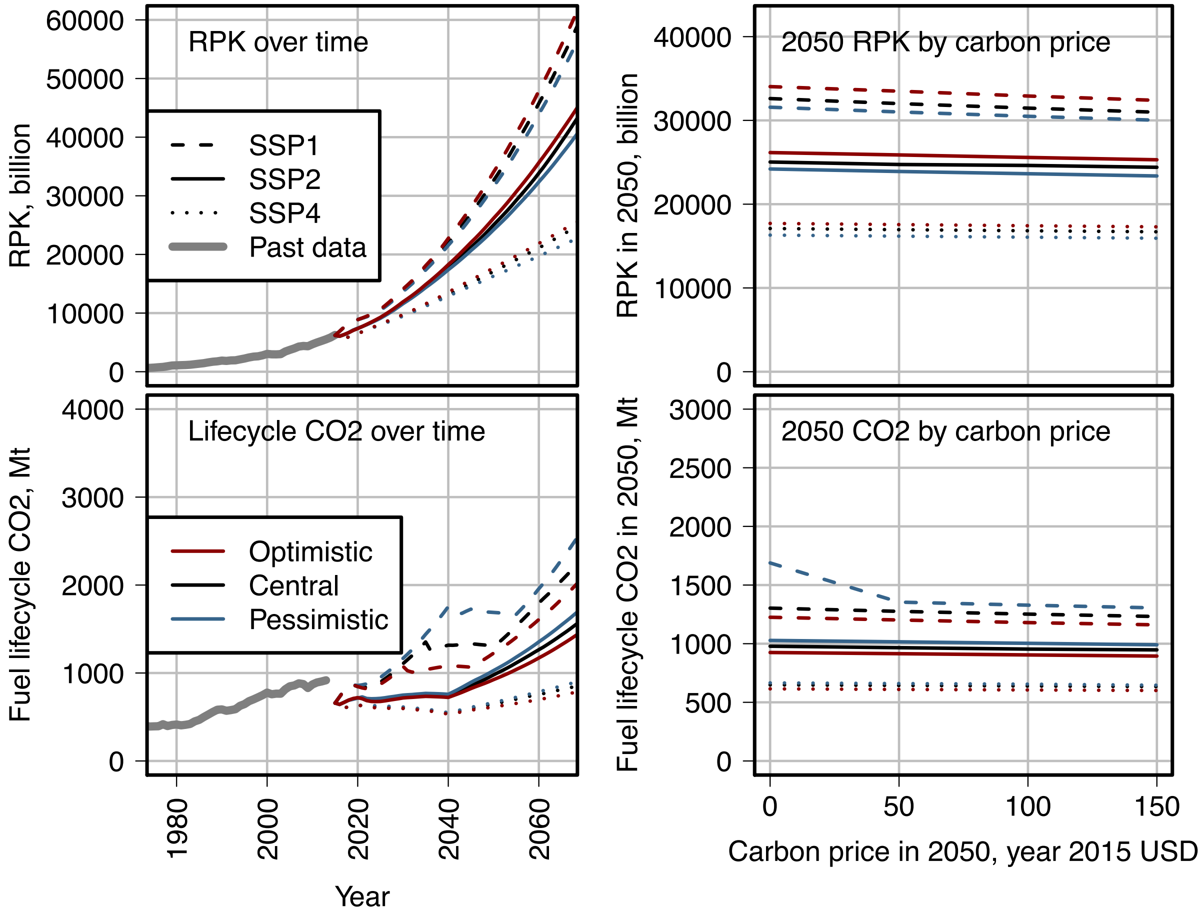
Example – global potential for CO2 reduction from jet engine aircraft

- Dray et al. (2018) based on technology characteristics from Schäfer et al. (2016)
- Examining what emissions reductions are possible/likely from:
  - Retrofits to existing fleet
  - Operational/maintenance changes
  - New airframes/engines (excluding options which would require significant infrastructure/network change)
  - Supply curve-limited drop-in biofuel uptake from cellulosic biomass
- Not included: electric aircraft, hydrogen, electrofuels, …

Example – global potential for CO2 reduction from jet engine aircraft

- Year-2050 fuel lifecycle CO_2 varies between 620 and 1690 Mt
  - Without biofuels, 1630 – 3400 Mt
- 1.9-3.0 %/year reduction in lifecycle fuel/RPK to 2050
  - Without biofuels, 0.8 – 1.6 %/year
  - US domestic narrowbody similar to Schäfer et al. (2016)
- Carbon price primarily affects emissions via RPK at levels modelled
  - Relatively small impact on technologies used
  - Higher impact if no biofuel

With biofuels



[Past data: ICAO, 2016; IEA, 2017]

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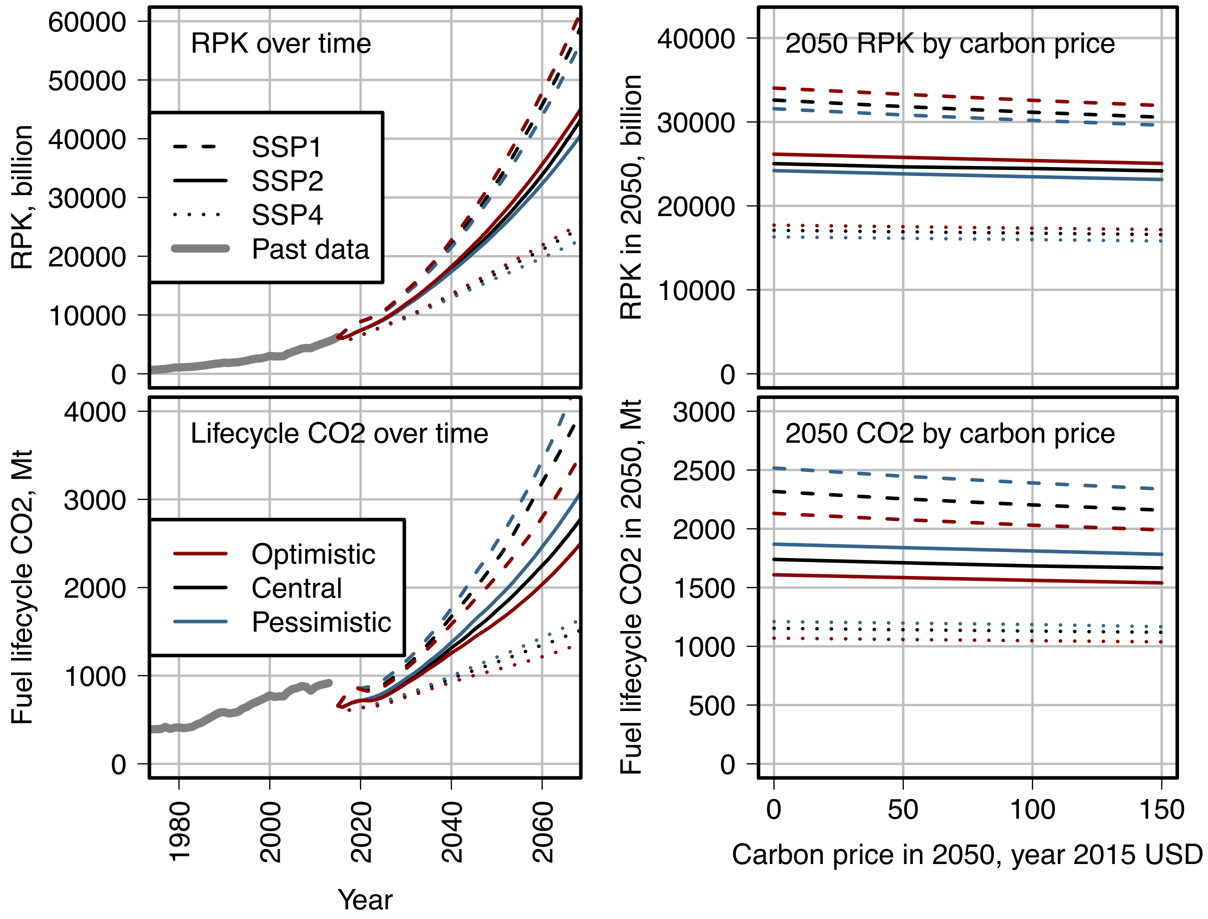
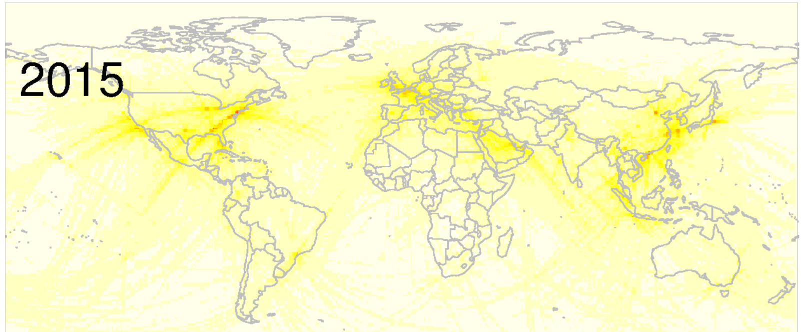
Without biofuels



[Past data: ICAO, 2016; IEA, 2017]

What else can we do with AIM2015?

- Some recent examples:
  - **Carbon leakage** (Dray & Doyme 2019) – assessing leakage impacts of UK-specific aviation policy for DfT
    - Found leakage can be over +/- 100%, strongly dependent on policy type, evaluation scope
  - **Assessing uncertainty** in future aviation sector emissions (Dray et al. 2019)
    - To 2050 CO_2 uncertainty can be ~ factor of 2, sensitivity to global/regional GDP
    - This has implications for the success of policies based on meeting a given CO_2 target
  - Looking at different ways of combining the **EU ETS and CORSIA**
    - Ongoing study for DG CLIMA
  - Looking at aircraft **scrappage policy** and if this could be supported by a carbon tax (Dray et al. 2014)
  - Assessing electricity requirements for **battery electric aircraft** networks (Schäfer et al. 2018)
  - Location-based **emissions inventories**



[Global aviation CO_2 SSP2 scenario, no radical new technologies, central technology lens]

The next step – airline competition modelling

- Why model airline competition?
    - Airlines set fare, frequency based on profit- (or market share-) maximization
    - This affects how they respond to system changes
        - E.g. cost changes, new competitors, new technology availability, …
- One key area affected by competition is response to new capacity
    - Airlines can respond by, e.g.:
        - Changing frequency on existing routes
        - Starting new routes
        - Changing aircraft types used to/from the airport
        - Changing fares
        - Changing operations, frequency, fleet and demand at other airports (potentially across the world)
    - These changes are interlinked, and have economic and environmental impacts
- The idea of ACCLAIM is to make a first order assessment of these changes with one integrated model

Modelling airline competition - methodology

Each airline is a player in an n-player noncooperative game. They attempt to maximise profit by adjusting the decision variables of airfares, flight frequency and choice of aircraft on routes within their network:

$$P_A = \boxed{\sum_{i\in \mathrm{ITN}_A} fare_i.pax_i + arev_A.pax_A} - \boxed{\sum_{j\in \mathrm{SEG}_A} \sum_{a\in \mathrm{CRFT}_j} opcost_{a,j}.freq_{a,j}} - \boxed{\sum_{j\in \mathrm{SEG}_A} \sum_{a\in \mathrm{CRFT}_j} paxcost_{a,j}.pax_{a,j}}$$

Revenue **Flight related costs** **Passenger related costs**

Passenger numbers are limited by each itinerary's market share of overall air travel demand between two locations:

$$pax_i \leq \boxed{\mathrm{MS}_i}.\boxed{\mathrm{D}_i}$$

Itinerary market share given by a (MNL) choice model:

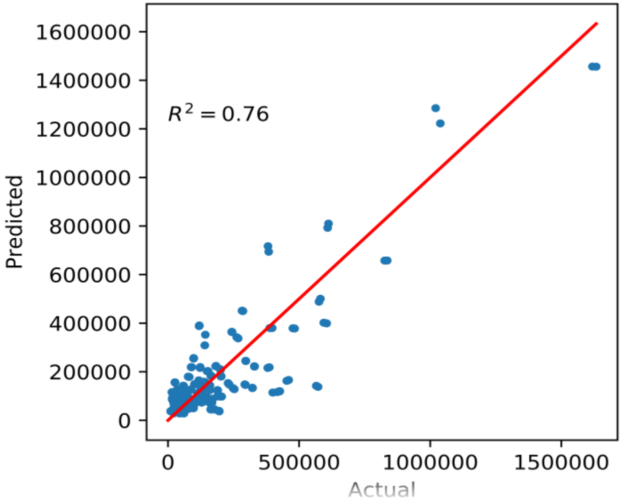
$$\mathrm{MS}_i = \frac{e^{U_i}}{\sum_{j\in \mathrm{ITN}_{o_i d_i}} e^{U_j}}$$

Overall city-pair air travel demand, given by a gravity model.

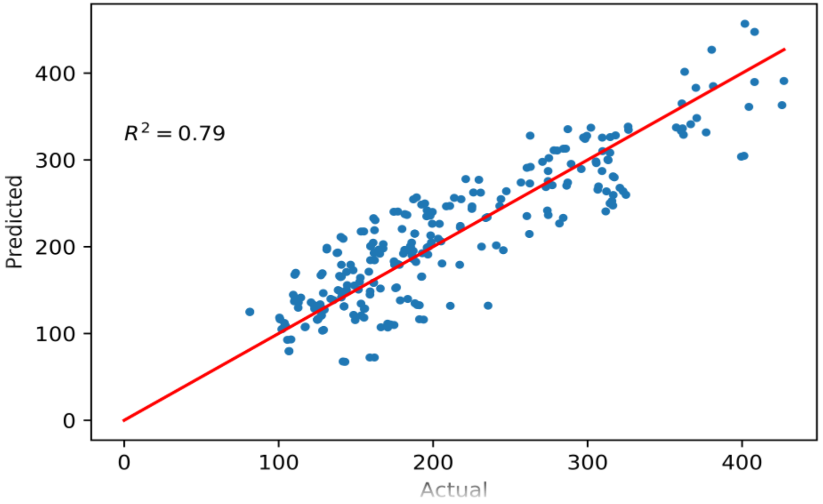
Constraints also include fleet, the number of seats available on each aircraft type, and airport capacity.

Example – Australian domestic market

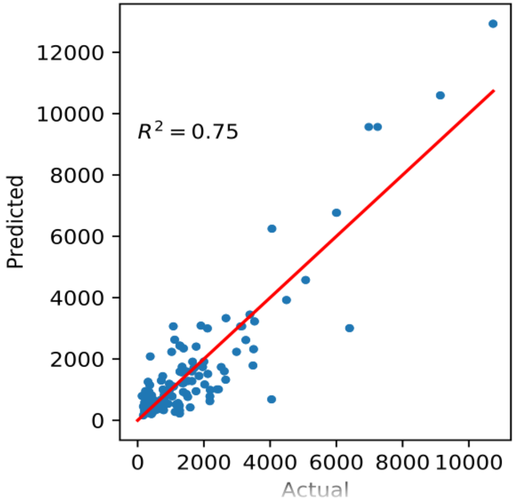
Predicted vs. Actual Passenger Numbers on each Segment



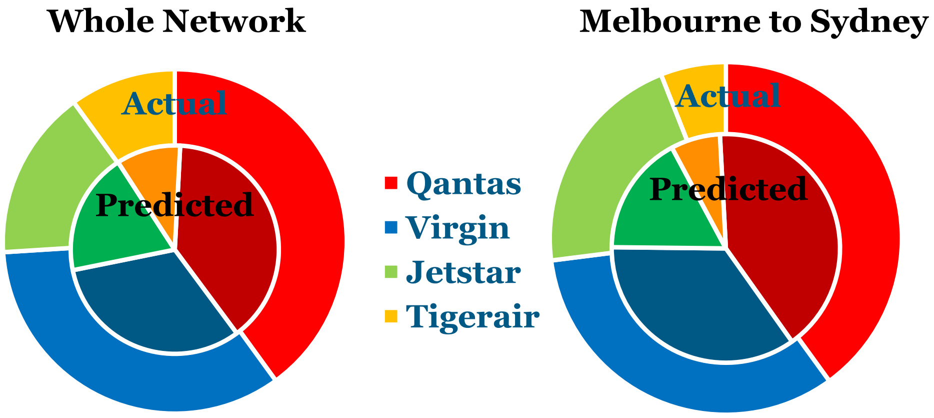
Predicted vs. Actual Segment Fares



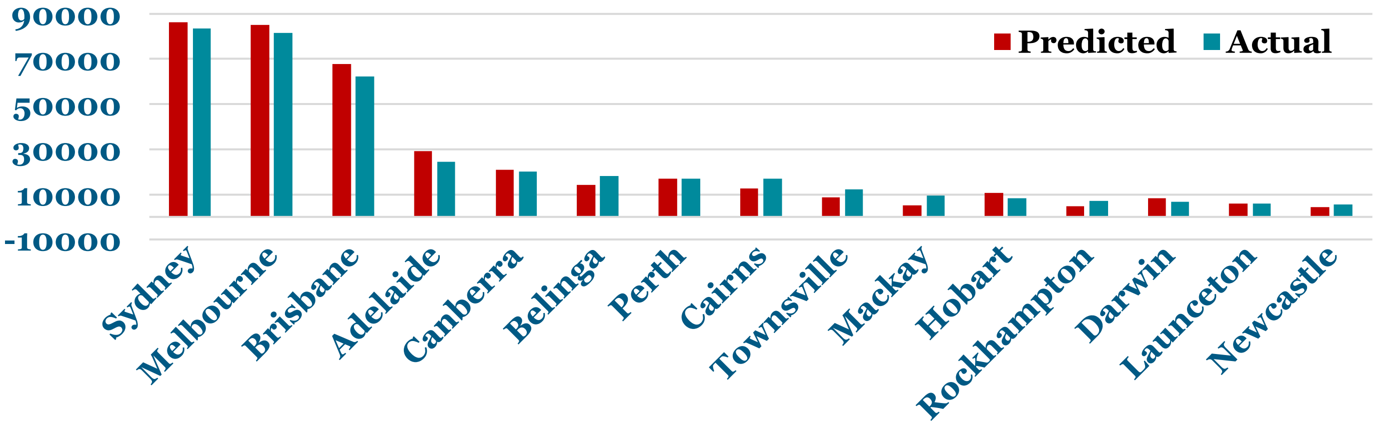
Predicted vs. Actual Segment Flight Frequency



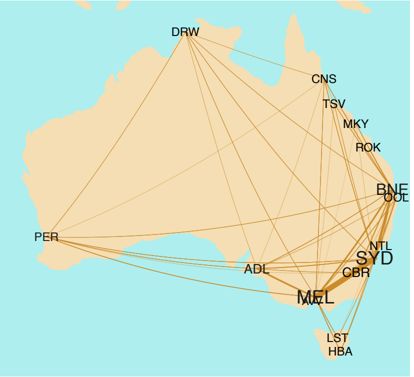
Market Share



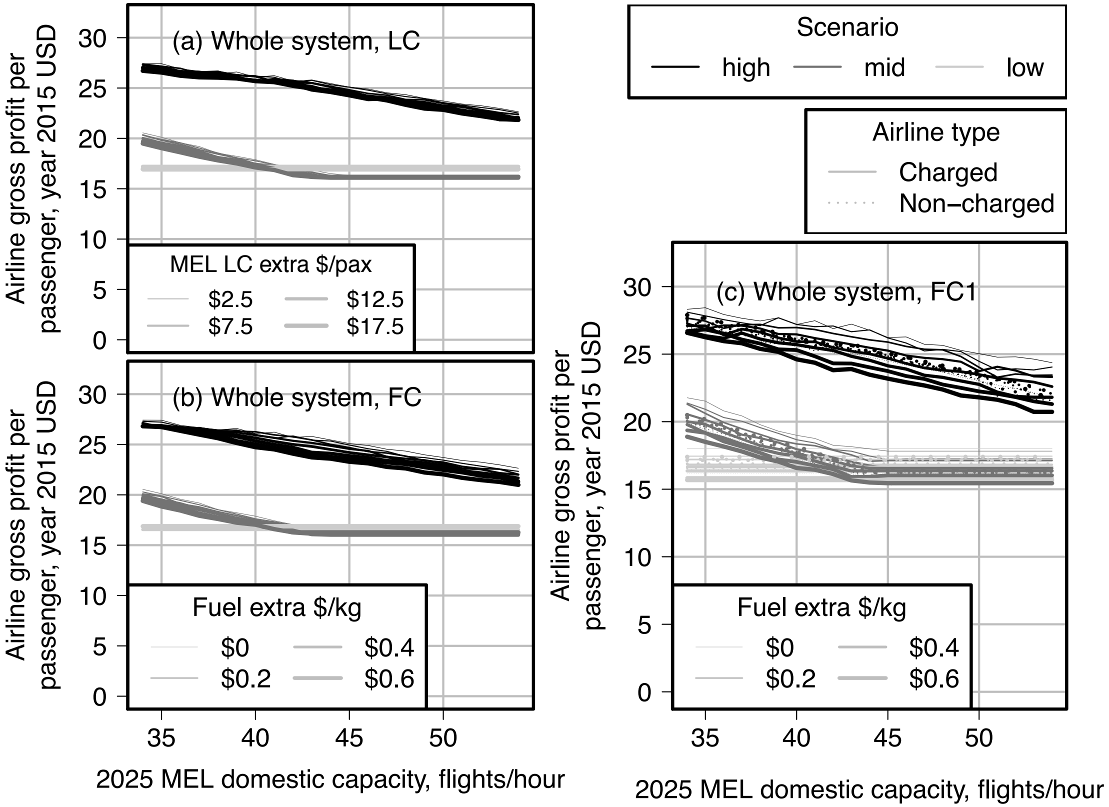
Domestic Departing Flights per Year



Example scenario – capacity expansion at Melbourne



- MEL is close to capacity with a new runway planned for 2025
  - Good test case to examine airline behaviour under capacity constraints
- System projected to 2025:
  - Generate high/mid/low demand scenarios with different socioeconomic projections
  - Estimate fleet using existing orders
  - Model a range of (domestic) capacity values, from no expansion (35 flights/hour), to 50% of new slots (55 flights/hour)
  - Also examine how this interacts with costs
- Endogenously generated insights include:
  - Capacity limits reduce cost pass-through level
  - Significant scarcity rents at constrained airports
  - Environmental/economic impact of airport expansion significantly affects other airports



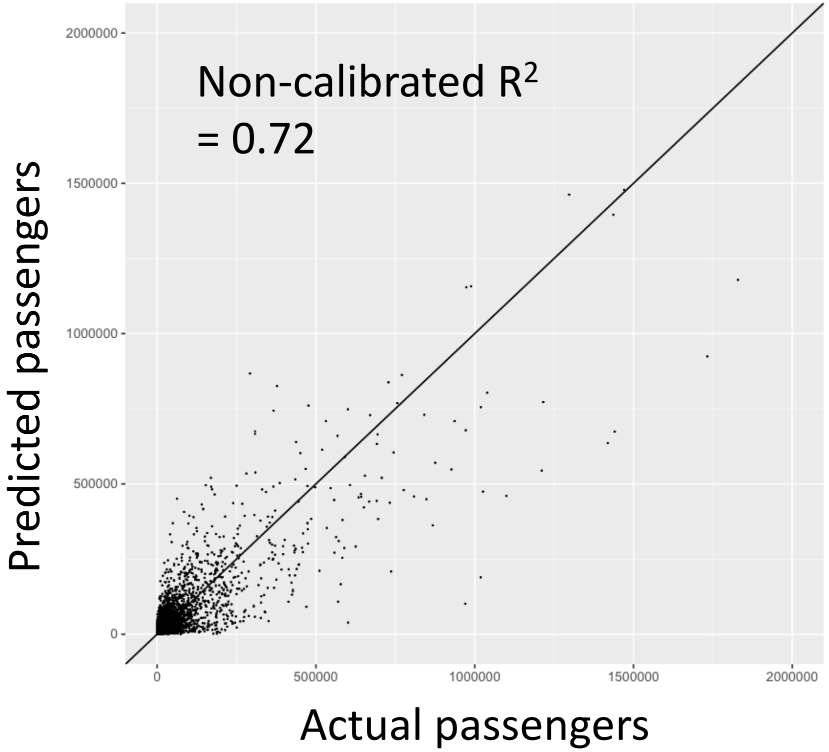
Airline behaviour model – ongoing work (North America)

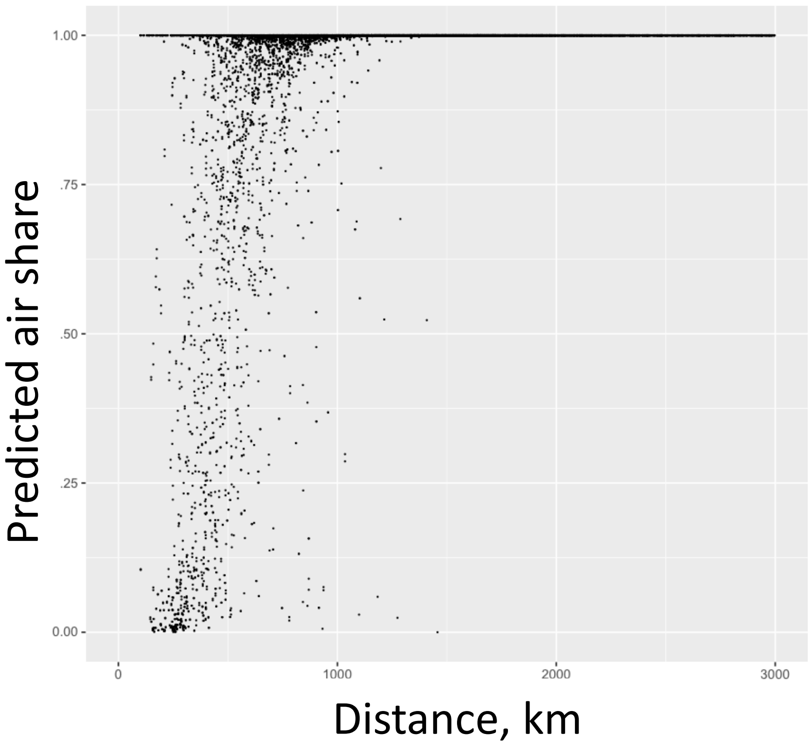
- Model is fully calibrated/tested for North America and Australia
- Larger world regions require more complex model
  - Importance of multi-airport systems and surface transport - > nested logit route/airport/mode choice
  - Need calibration factors to account for income distributions, ‘other’ historical links between cities
  - Larger computational problem -> parallelisation
- Example for North America – (hypothetical) expansion at La Guardia
  - Illustrates multi-airport system dynamics

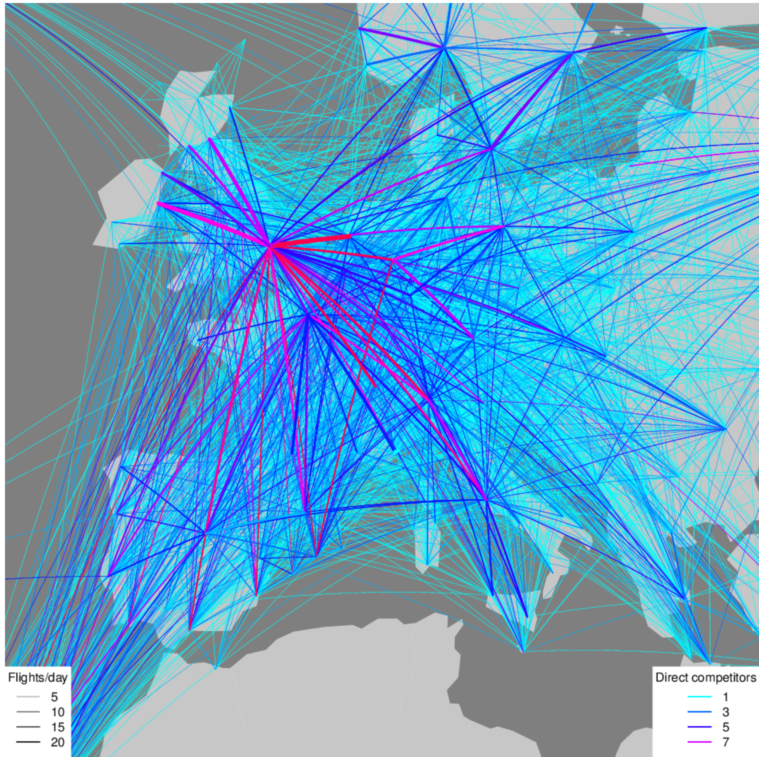
	Pre-Expansion			**Post-Expansion**		
Airports	Departures (thousand)	Passengers (million)	Airfares ($)	Departures (thousand)	Passengers (million)	Airfares ($)
LGA	194	13.7	227	215	15.1	225
EWR	161	11.7	260	163	12.1	260
JFK	110	10.7	239	113	11.1	234
Other	17	1.2	240	17	1.3	239
NY Total	482	37.3	240	508	39.6	238

Airline behaviour model – ongoing work (Europe)

- Intra-Europe and intra-Middle East/Africa at validation stage
    - For Europe, model includes train alternatives, common language, visa requirements etc.
    - Ongoing development for other global route groups, including transcontinental
- Once validated, world regions can be linked to examine issues that have global impact
    - E.g. changes to major hub airports with intercontinental flights


Non-calibrated R^2 = 0.72





What else can we do with the Airline Behaviour Model?

Some examples:

- **Technology uptake**
  - Can look at what routes airlines would deploy a new technology on given technology and network characteristics
  - E.g. what design range for a hybrid electric aircraft would be most successful in a given market?
- Response to **new airline** entering the market
- Testing how **new routes or network structures** would affect airline profit
  - Can be combined with new aircraft with different capabilities
- Assessing how emissions respond to policies that are applied differently across airlines (e.g. by nationality)
- Assessing ideal location for a **new hub airport** (in terms of CO_2, airline profit, and/or local emissions/noise)

Any questions?

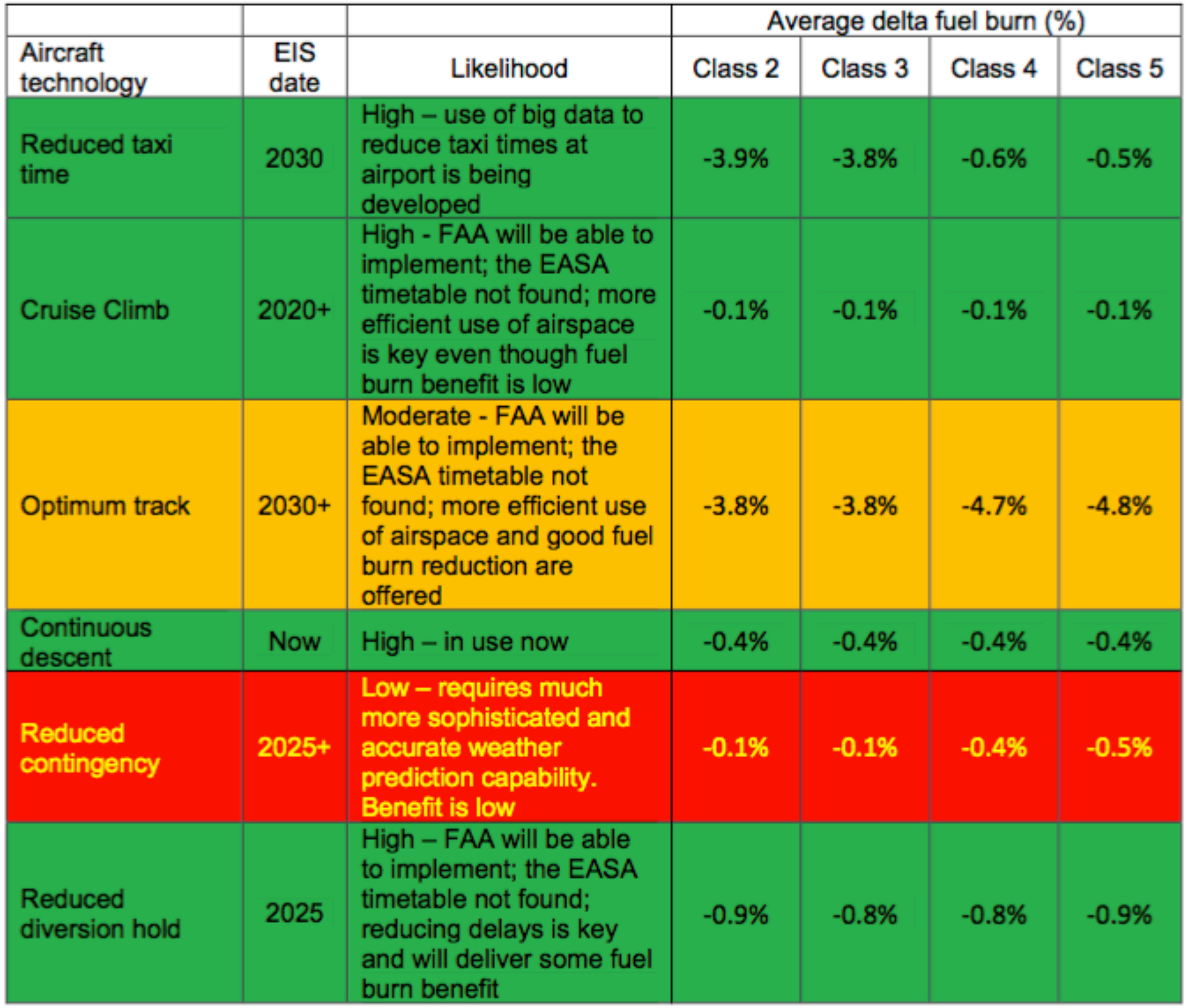
More information: www.atslab.org

Appendix: how does/could this interact with ATM?

- Currently both models use a highly aggregate representation of the ATM system
  - Track extension factors to account for distance flown beyond great circle
  - Non-lateral inefficiency factor to account for vertical/speed-related extra fuel use
  - Improvements in operational efficiency then reduce these factors
  - Runway capacity (rather than airspace, terminal, etc.) is assumed to be the main capacity bottleneck
- Potential exists to add more detailed airspace modelling
  - E.g. could look at/project demand by airspace sector and how this responds to different policies
  - Would require time/data, however

Appendix: how does/could this interact with ATM?

- Also potential to look in more detail at aggregate benefits from ATM improvements
- Applying these to AIM allows second-order impacts to be estimated, e.g. :
  - Reduced fuel use -> reduced airline operating costs -> lower ticket prices -> higher demand
  - Change in fuel, carbon and enroute costs -> change in technology choice



			Average delta fuel burn (%)			
Aircraft technology	EIS date	Likelihood	Class 2	Class 3	Class 4	Class 5
Reduced taxi time	2030	High – use of big data to reduce taxi times at airport is being developed	-3.9%	-3.8%	-0.6%	-0.5%
Cruise Climb	2020+	High - FAA will be able to implement; the EASA timetable not found; more efficient use of airspace is key even though fuel burn benefit is low	-0.1%	-0.1%	-0.1%	-0.1%
Optimum track	2030+	Moderate - FAA will be able to implement; the EASA timetable not found; more efficient use of airspace and good fuel burn reduction are offered	-3.8%	-3.8%	-4.7%	-4.8%
Continuous descent	Now	High – in use now	-0.4%	-0.4%	-0.4%	-0.4%
Reduced contingency	2025+	Low – requires much more sophisticated and accurate weather prediction capability. Benefit is low	-0.1%	-0.1%	-0.4%	-0.5%
Reduced diversion hold	2025	High – FAA will be able to implement; the EASA timetable not found; reducing delays is key and will deliver some fuel burn benefit	-0.9%	-0.8%	-0.8%	-0.9%

[Data: ATA and Ellondee report for CCC/DfT, 2018]