Modelling airline behaviour to assess adoption and use of novel aircraft technology

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Background

- Aviation is currently responsible for 3.5% of anthropogenic effective radiative forcing (Lee et al. 2020)
  - Around 90% of civil aviation impacts are from passenger aircraft (plus hold freight) and around 10% freighters
- Long-term industry projections (e.g. Airbus, Boeing) were for continued rapid global demand growth
  - Covid19 will offset this demand growth but probably not eliminate it
  - The main driver is increases in global incomes, particularly outside North America/Europe

$$\underbrace{CO_2}_{CO_2\text{ Emissions}} = \underbrace{\frac{CO_2}{E}}_{\text{Fuel Composition}} \cdot \underbrace{\frac{E}{RTK}}_{\text{Energy Intensity}} \cdot \underbrace{RTK}_{\text{Air Transport Demand}} - Offsets$$

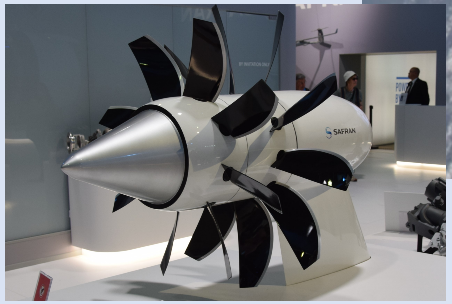
	CO_2 Emissions	Fuel Composition	Energy Intensity	Air Transport Demand
1980-2015:	**+2.2%/yr**	**0**	**-3.2%/yr**	**+5.4%/yr**
2015-2050:	**+2.6%/yr**	**0**	**-1.6%/yr**	**+4.2%/yr**

[Data: IEA, 2019; ICAO, 2019; Dray et al. 2018]

- If 'business as usual' trends continue, aviation emissions will likely increase relative to other sectors
  - E.g. CCC (2019) project aviation to be the UK's **highest-emitting sector** by 2050

Decarbonising aviation

- Deep decarbonisation within the aviation sector (i.e., excluding offsets) will likely require radical technology change
  - Either rapid increase in drop-in biofuel/PTL
  - Or changing both aircraft and fuel (electricity, hydrogen, possibly LNG)
  - The latter case may allow contrails/local emissions to be significantly reduced as well
- But any radical technology change faces uptake barriers
  - Aircraft development, fleet turnover and adoption timescales
  - If conventional alternatives are also available, will airlines use it?
  - Will airlines who adopt the technology use it in a way that is consistent with emissions reduction goals?
- We can also look at the problem from the other direction: what characteristics would a new-technology aircraft have to have to be successfully adopted and used?
  - To do this we need to understand airline choices and behaviour…



[Image sources: NASA, 2018; Airbus, 2020; Wikimedia Commons]

Modelling airline behaviour

- Why look at airline competition?
  - Airlines set fare and frequency and make technology choices based on profit- (or market share-) maximization
  - This affects how they respond to system changes
    - E.g. cost changes, new competitors, new technology availability, …
- For example: new capacity at a congested airport
  - 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
- Similarly, when a new technology becomes available, competition affects where, how and if it is used
  - Can an airline increase its profits by using the new technology?

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:

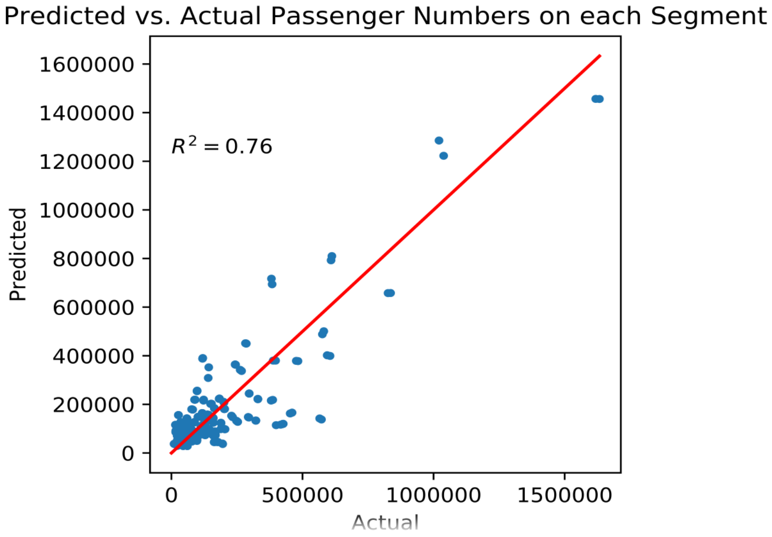
$$\mathrm{MS}_i = \frac{e^{U_i}}{\sum_{j \in \mathrm{ITN}_{o_i d_i}} e^{U_j}}$$

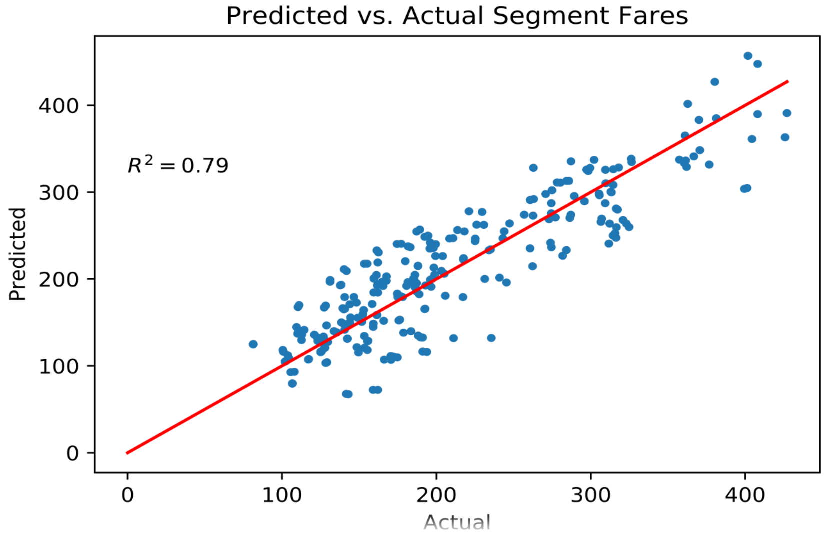
Overall city-pair air travel demand, given by a gravity model.

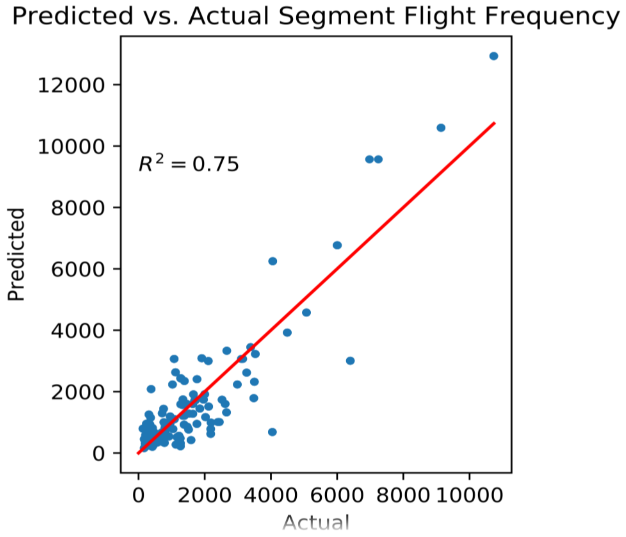
Constraints also include fleet, the number of seats available on each aircraft type, and airport capacity.

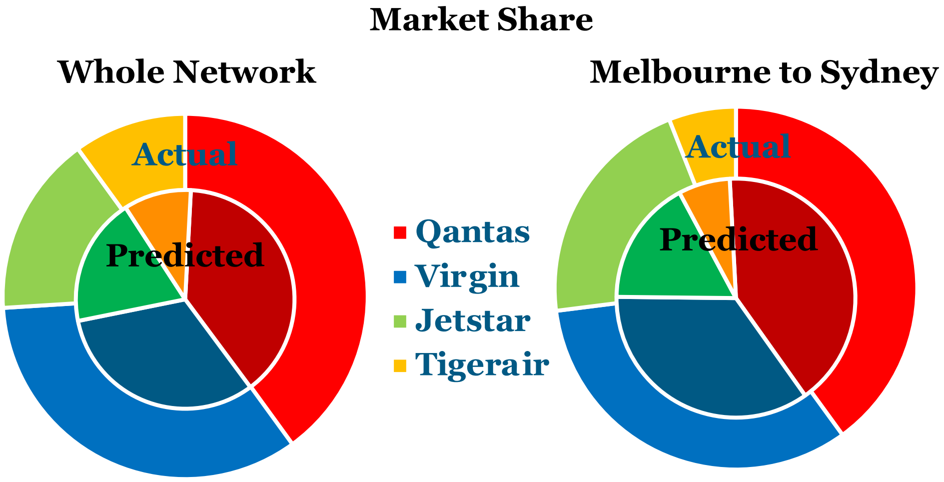
Example - the Australian domestic aviation system

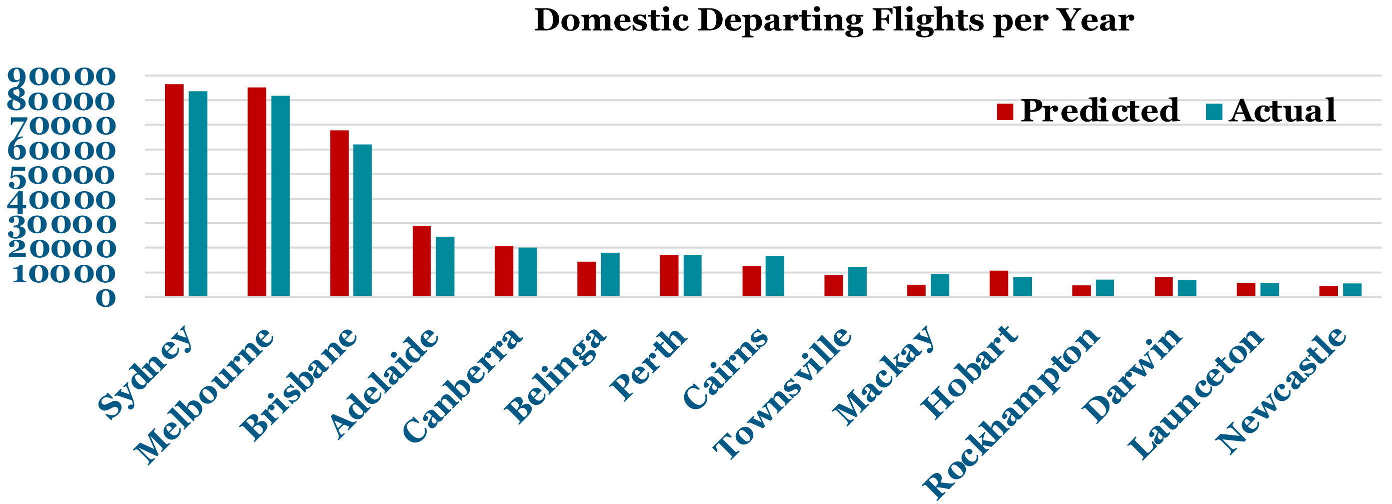
[Doyme et al. (2019)]



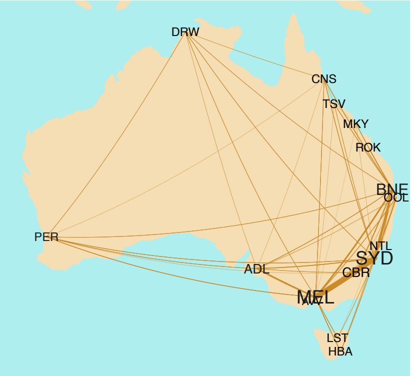






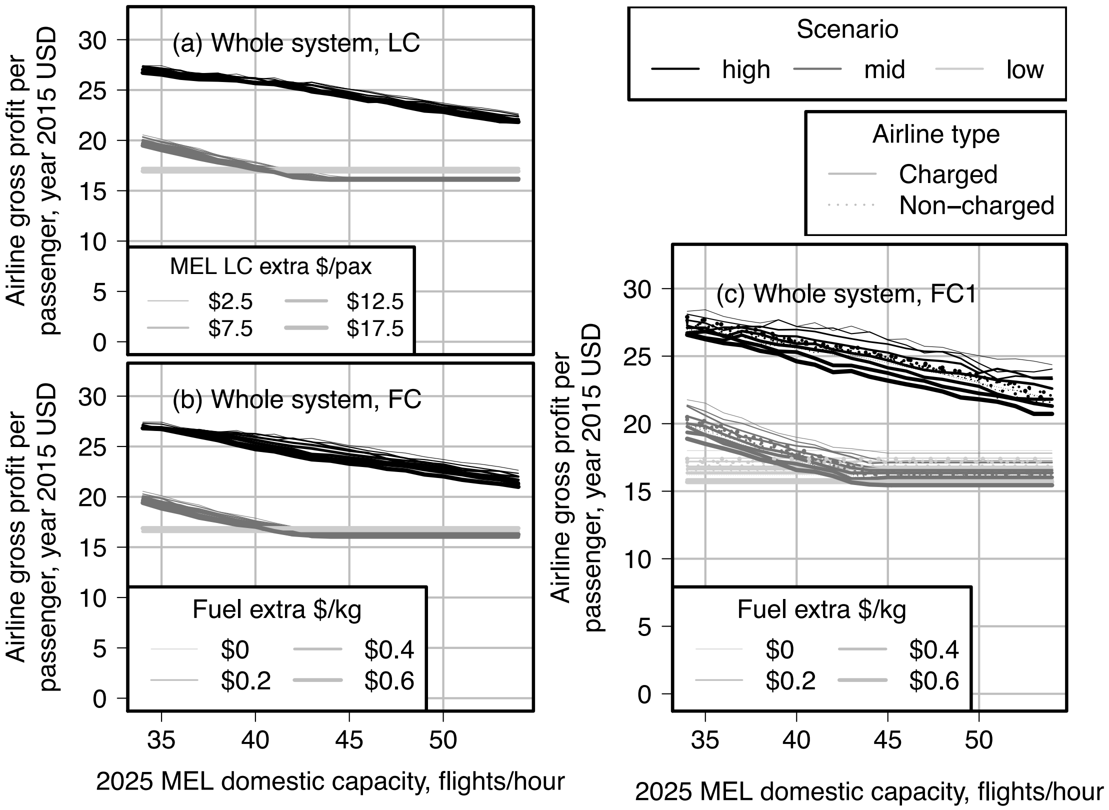


Example scenario - capacity expansion at Melbourne



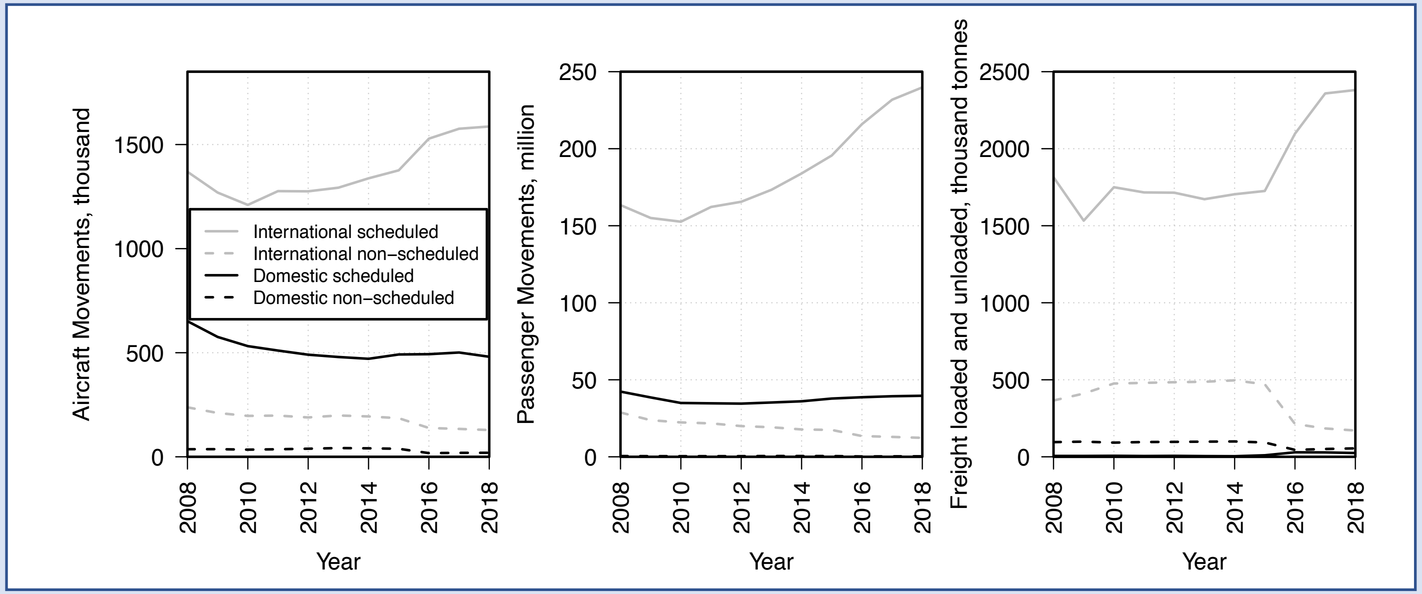
- MEL is close to capacity with a new runway planned for 2025
  - Good test case to examine airline behaviour under capacity constraints
- System projected to 2025:
  - Generate high/mid/low demand scenarios with different socioeconomic projections
  - Estimate fleet using existing orders
  - Model a 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

[Dray et al. (2020)]



Technology case study - the UK domestic aviation system

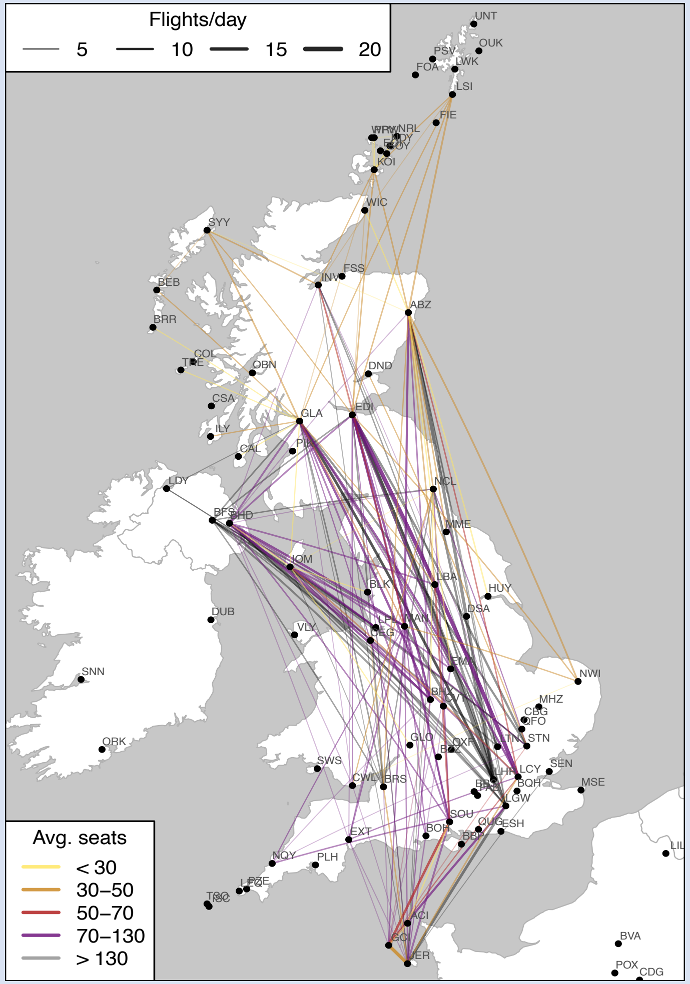
- Domestic demand was flat/decreasing even before Covid19
- However, projections often assume growth (e.g. DfT, 2017)
- Heavily affected by recent bankruptcies (e.g. Flybe, Thomas Cook)



[Data: CAA, 2020]

- Three challenges:

Environmental impact | Regional connectivity | Supporting UK aerospace



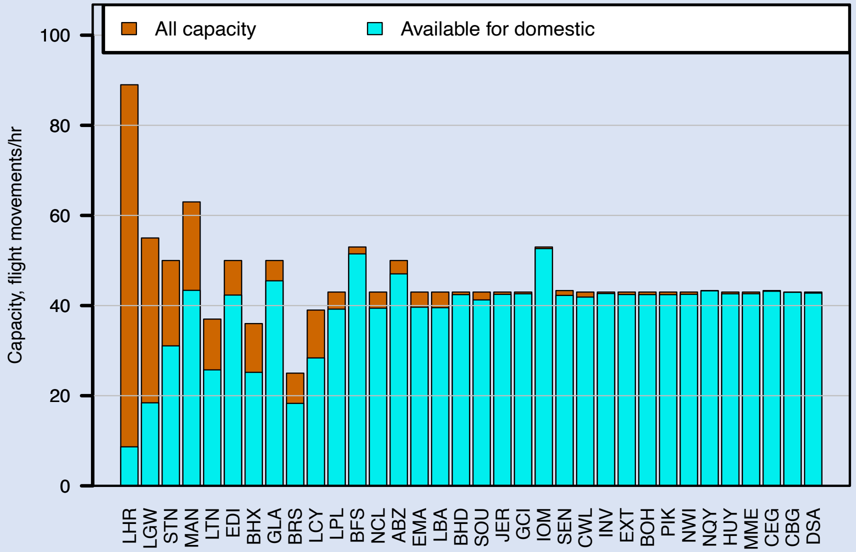
[Data: Sabre, 2017]

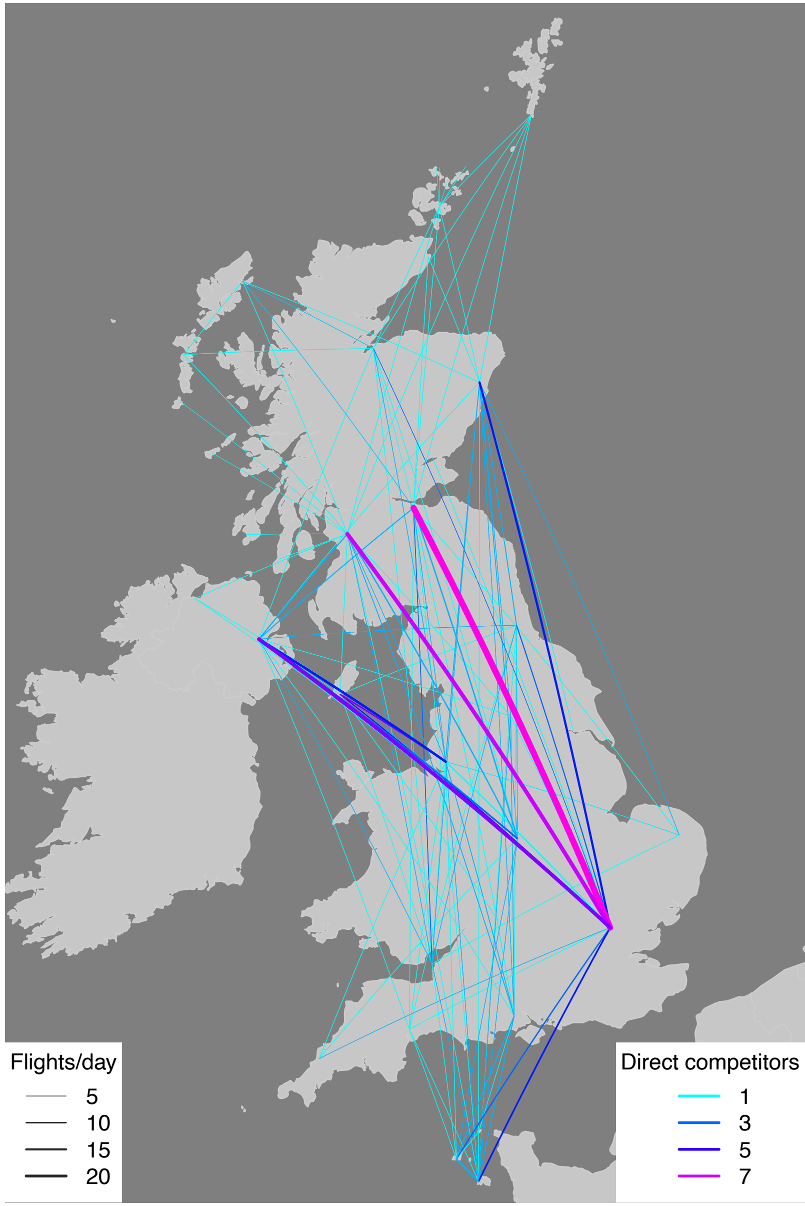
NAPKIN project

- 18-month Innovate UK-funded collaboration between UK manufacturers, airports and academics
- Key questions include:
  - Could electric (or other alternative technology) aircraft be feasible on UK domestic routes?
  - How would electric aircraft affect the business case for regional routes?
  - What characteristics would an aircraft design have to have to be successful in this context?
    - E.g. range, minimum runway length, seat capacity, noise, …
  - Many different components:
    - Aircraft designs
    - Operational characteristics for a single flight
    - **Potential use in the UK domestic network** ← This talk
    - Public acceptance
  - This is an ongoing project and only very preliminary results so far

UK domestic system – airlines

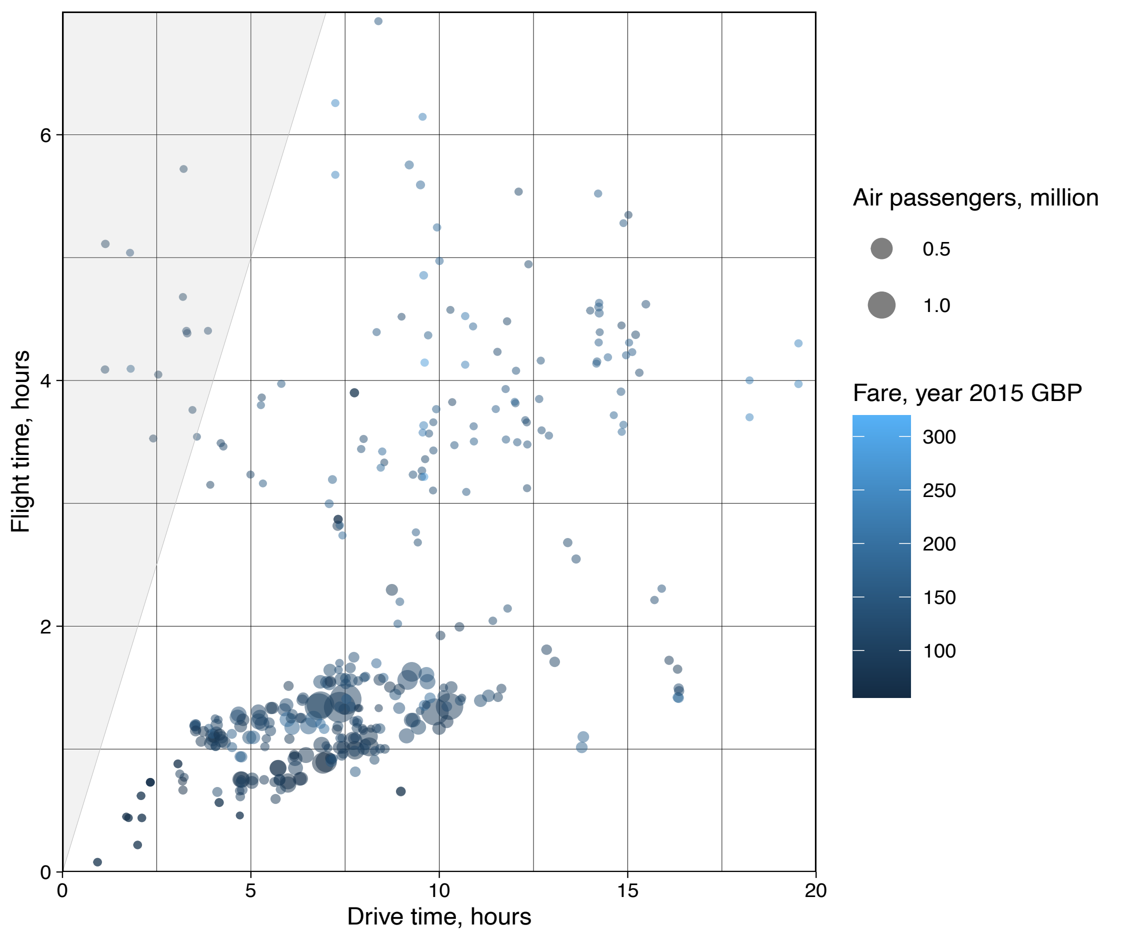
- Once airlines that are co-operating are grouped together, only a few competitive routes
  - Other routes include a mix of regional and remote/subsidised flights
  - Mix of legacy carriers with diverse fleet and LCCs with homogenous fleet
- Key factors affecting airline decisions include:
  - Airport capacity (particularly in the London area)
  - High density of airports leading to multi-airport system choices – e.g. London, Glasgow, Belfast
  - Some restrictions on operations that may affect technology uptake
    - Short runways
    - Curfew impact on number of flights/day
    - Noise regulations
  - Fuel costs are relatively small due to short distances





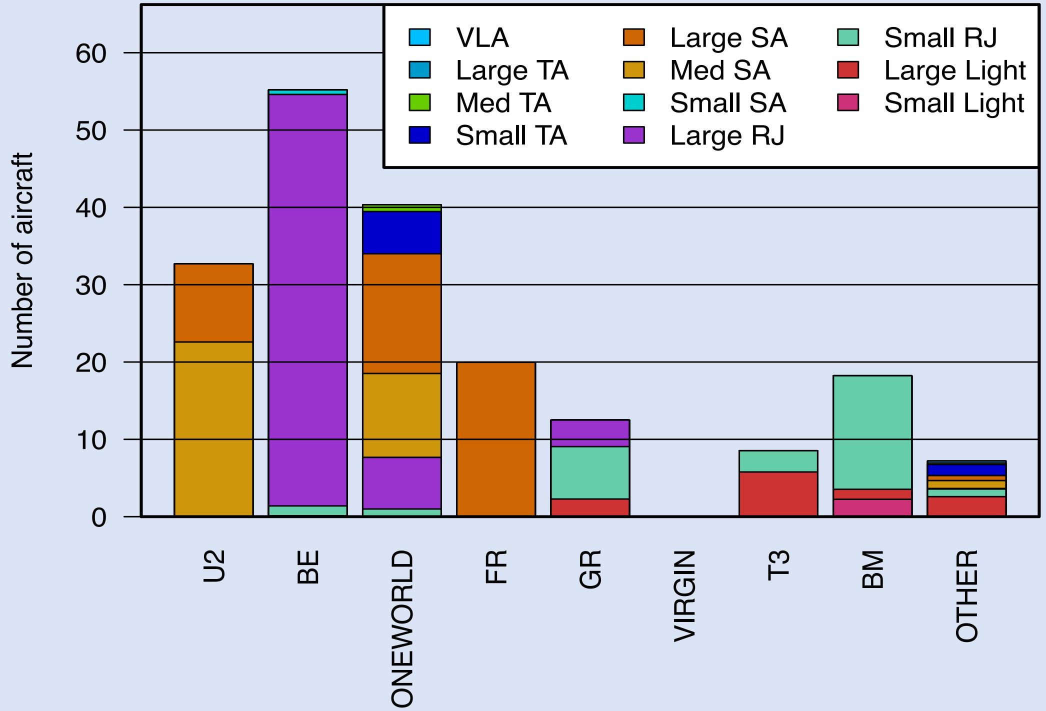
UK Domestic System - Passengers

- Key passenger choices:
  - Mode choice – air, rail, road all competitive on many routes
  - Which airport to fly from/to in multi-airport systems
  - Which airline to fly with (often choice of full service/LCC/regional carriers)
  - For remoter regions, may be a choice of less frequent direct route vs. more frequent one-stop itinerary
  - If electric aircraft were introduced, may be demand/fare effect from travellers who are willing to pay extra for a low-carbon option (survey ongoing)
- These choices are interlinked
  - Current passenger demand model is a 3-level nested logit model (route/airport/mode choice)
  - Currently at city-pair level but working towards smaller region-pair to capture multimodal journeys



Key constraints

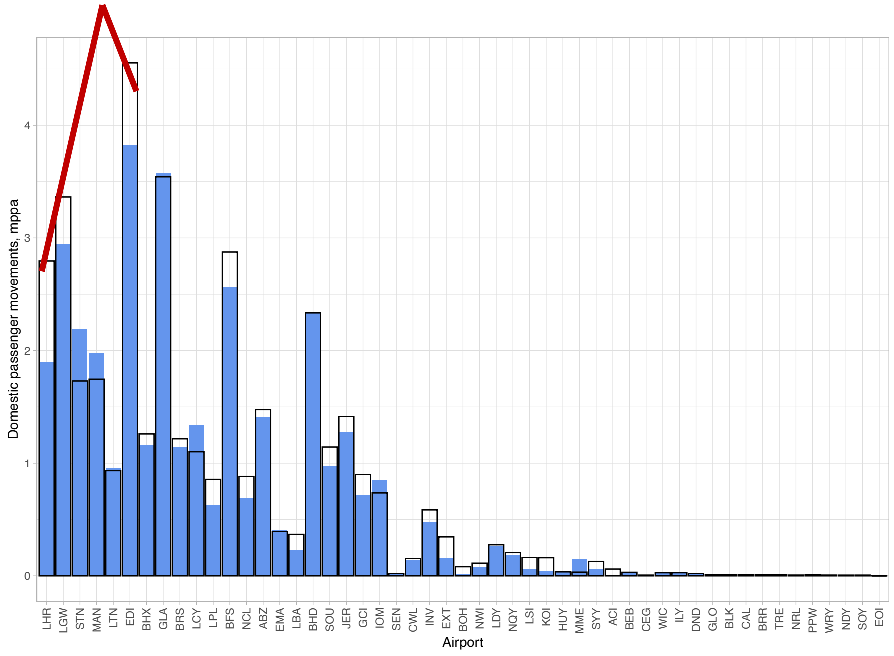
- Baseline: airlines are limited by the **fleet** they have available
  - E.g., increasing frequency on one route → decreasing frequency on another
  - Airlines with homogenous fleets (e.g. LCCs) have lower fleet-type costs but less flexibility
- Airlines are limited by the **capacity** available at the airports they fly to
  - Runway capacity (slots) is typically the bottleneck
  - This constraint means airlines may use larger aircraft than they would prefer to and from congested airports
- Airlines are limited by the behaviour of their **competitors**
  - E.g., if only one airline experiences a change in costs, they are less likely to pass through those costs to ticket price if they would lose market share by doing so
- What happens if we give airlines the option of alternative technology aircraft?
  - Outcomes will depend on costs, capabilities, and how these interact with system constraints

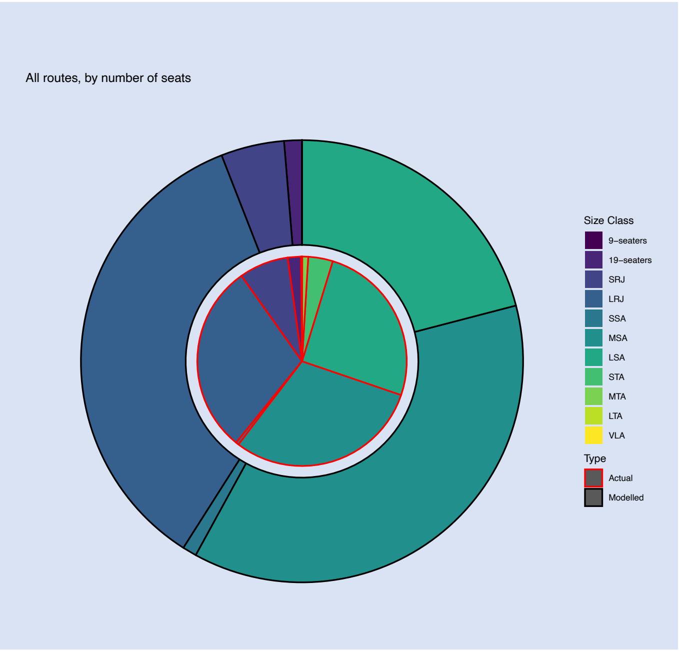


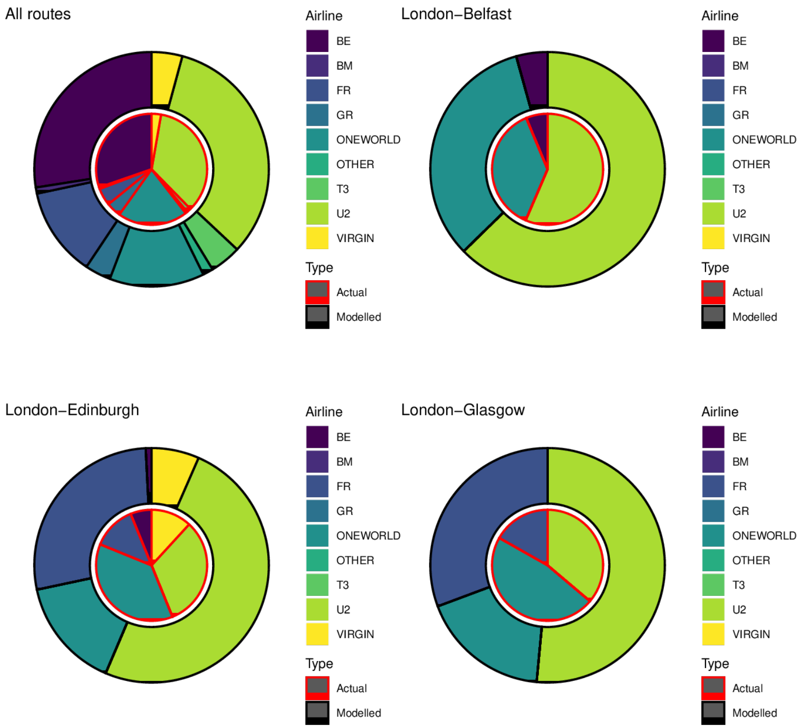
Solving the model and validation

- Each airline in turn optimises its profits across its network (IBM cplex) until equilibrium is reached
- Aggregate outcomes match well to actual values but some differences at a segment level
  - Passengers who take a domestic flight to comment with an international flight are not covered
  - Not all airlines are making a profit!

Domestic-international connections

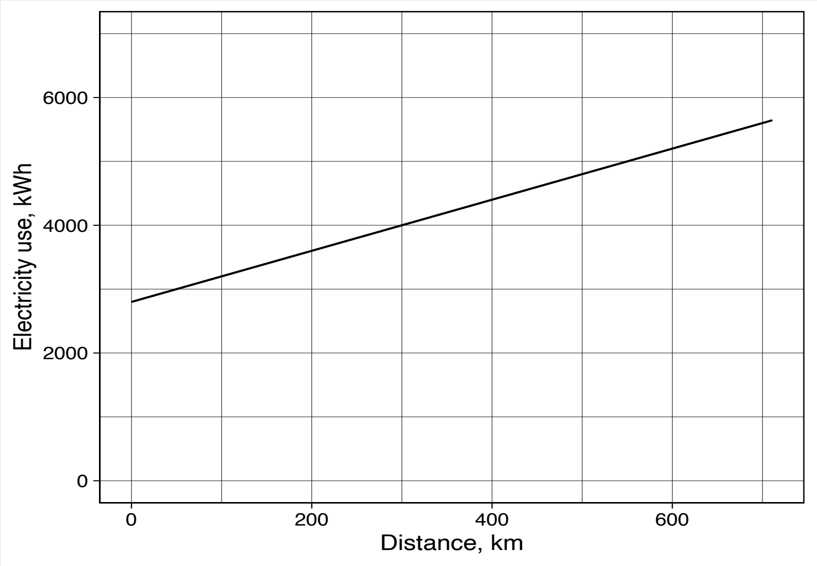




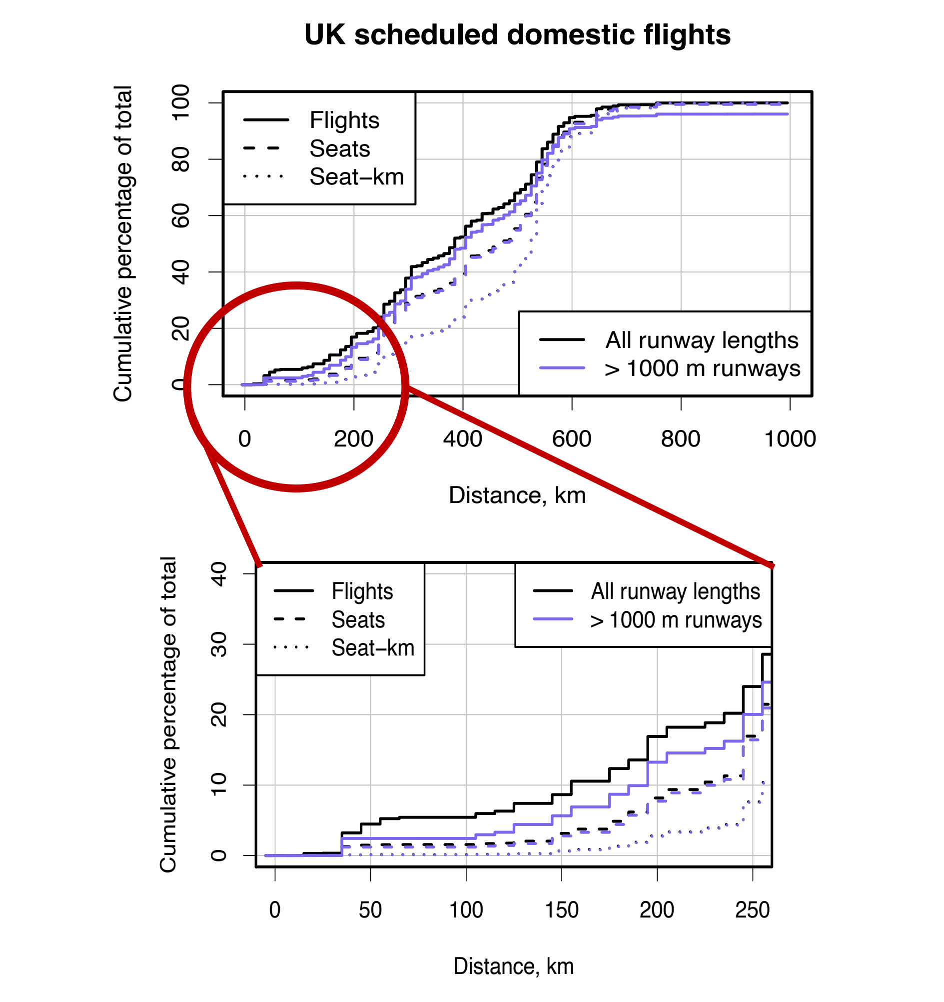


Making an alternative technology available

- Likely characteristics of early electric aircraft:
  - Small (modelled – 24 seats*)
  - Range-limited (modelled – 711 km)
  - Might have different requirements on runway length to conventional alternatives (modelled – 1500 m)
  - Cost differences including battery replacement, industrial electricity price (e.g. Schäfer et al., 2019)



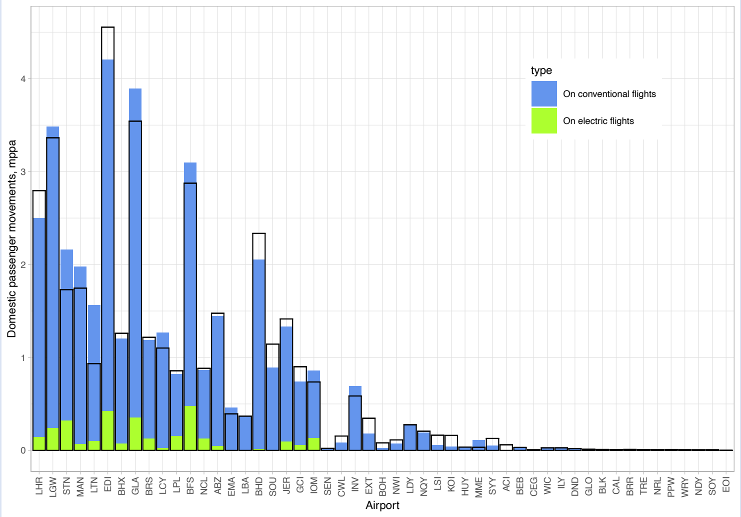
- Might be subject to different charges
  - Some airports have suggested zero (initial) landing costs
  - Noise (and noise costs) may differ
  - MTOW-based charges may be higher

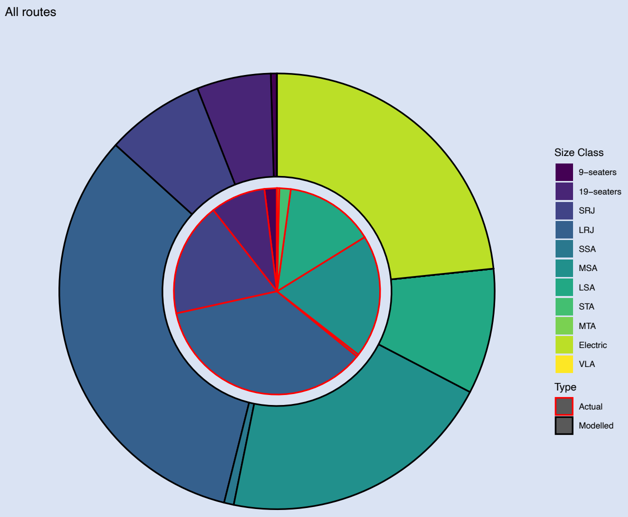


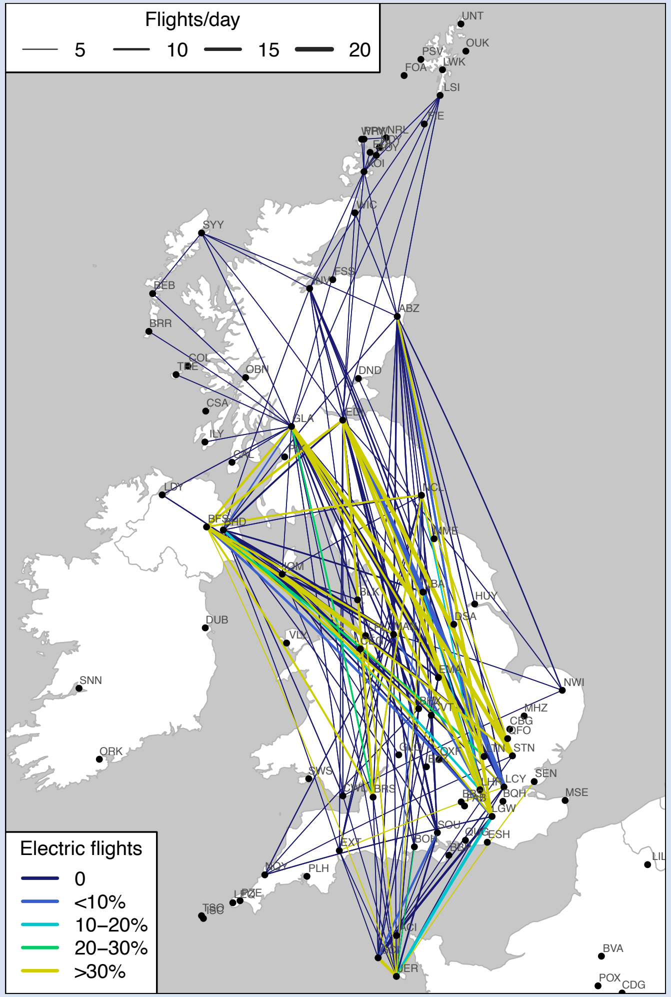
* Note these are dummy values to test model function, not project outputs; source: Hepperle (2012)

Making an alternative technology available

- These electric aircraft are made available to airlines, who can choose to use them if they can increase their profits by doing so
    - Some policy support assumed, e.g., no extra landing cost from higher MTOW
- The airline behaviour model tracks **if** they are used (for a given fuel price and set of electric aircraft characteristics) and **where/how** they are used
    - E.g. initial test runs → used to provide more frequent service on competitive routes with no ground alternative



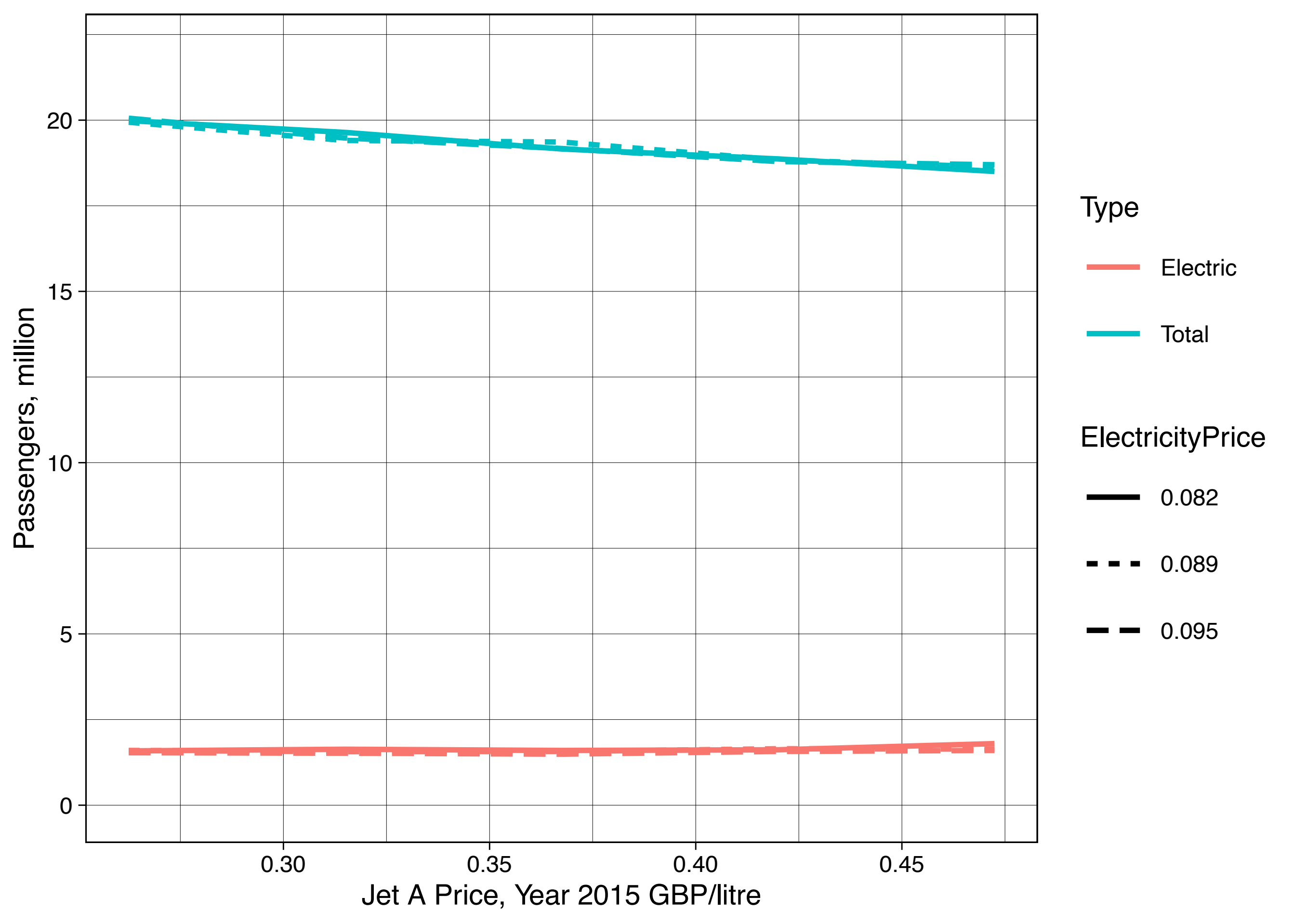




Making an alternative technology available

- How does this depend on system characteristics?
  - Fuel/electricity price dependence is relatively small
  - This is because these flights are short-haul and other cost components are important
    - E.g. Landing costs, maintenance, passenger taxes
  - In practice this may mean that uptake is mostly dependent on:
    - Airport/government decisions about per-flight/ per-passenger charges
    - Aircraft capabilities – e.g. does the design have sufficient range?

Electricity and Jet A prices



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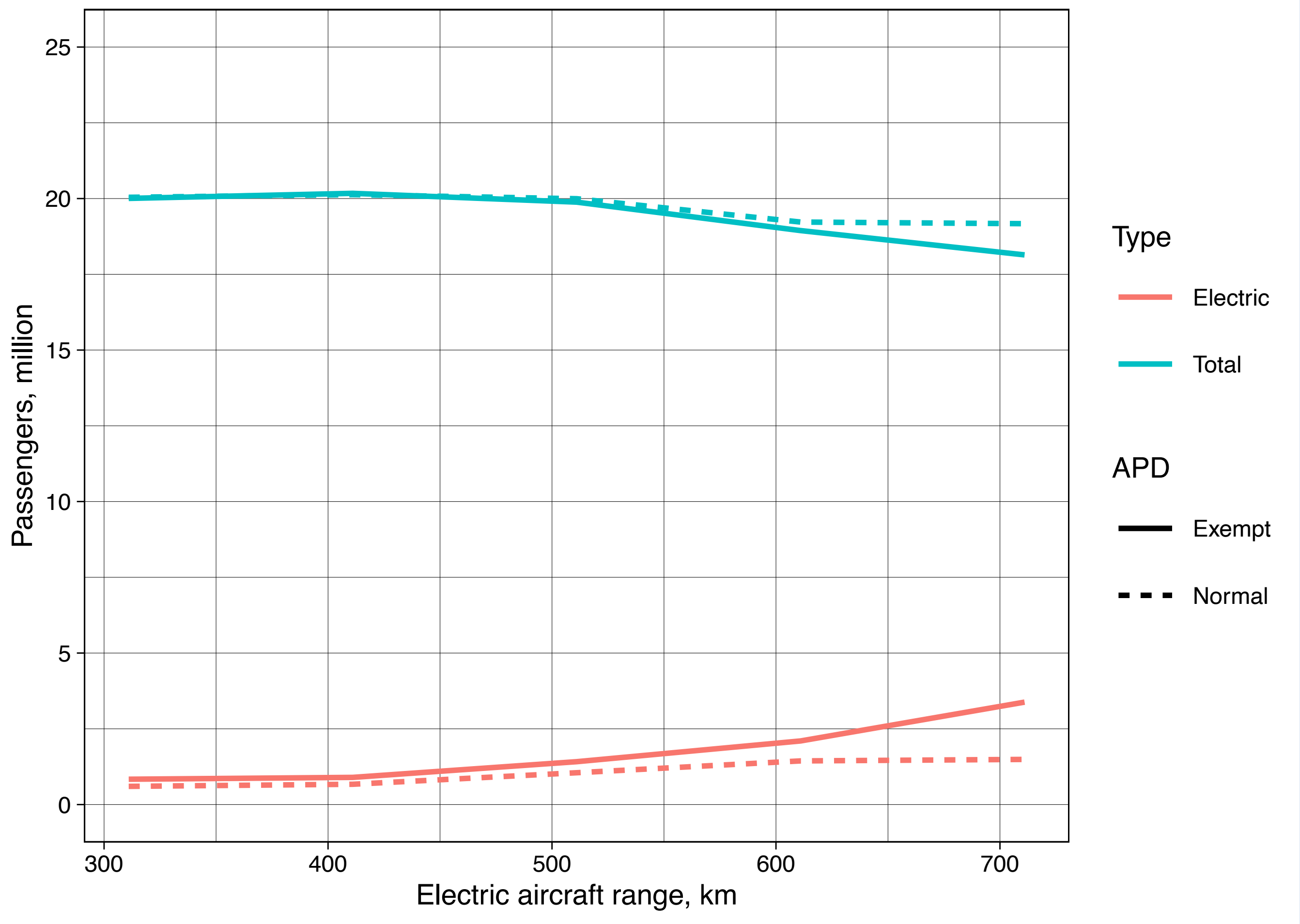
Range and Electric Aircraft APD Eligibility



Upcoming adjustments

- This is a work in progress – NAPKIN began November 2020
- Updated demand model under construction
  - Capturing the impact of passengers making a ground journey to a different city to take a (domestic) flight
  - Divides the UK into smaller regions, with access time to different airports considered
- Improving representation of conventional technology in smaller size classes
  - E.g. competing aircraft are a mixture of turboprops and jet aircraft
- Considering other aspects of integrating new technology into current system
  - Noise (cabin/airport-area) – difficult as noise characteristics may be significantly different
  - Passenger acceptance / WTP for green aviation – surveys upcoming
- Testing different technologies
  - E.g. short range hydrogen fuel cell retrofit aircraft
- Further model development (including consideration of much larger world regions and airport infrastructure dynamics) as part of the upcoming ToZCA project

In conclusion: technology characteristics

- Some conclusions
  - **These are initial/tentative conclusions from the first stage of the project**
  - Electric aircraft at literature characteristics could be commercially feasible, however:
    - Short range is a potential barrier to adoption
    - Because initial routes are very short-haul, uptake is relatively insensitive to fuel and electricity prices
      - Factors such as landing costs and passenger taxes have a large impact if they are a greater fraction of operating cost at short distance
    - Because initial aircraft are small, some indications that cost-effective use may be on short-haul routes where high frequency is an advantage and ground competition is limited
      - E.g. routes that are relatively high demand/competitive
      - Limited or no road alternative
      - Low-demand island routes are often NOT feasible (e.g. short runways)
  - **What does this mean for global aviation externalities?**
    - Very little (initially) - the substituted flights are a tiny fraction of global totals…
    - BUT can help as part of a pathway towards more general uptake/acceptance of alternative technology

More information: www.atslab.org