The Global Potential for CO_2 Emissions Reduction from Jet Engine Passenger Aircraft

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Background

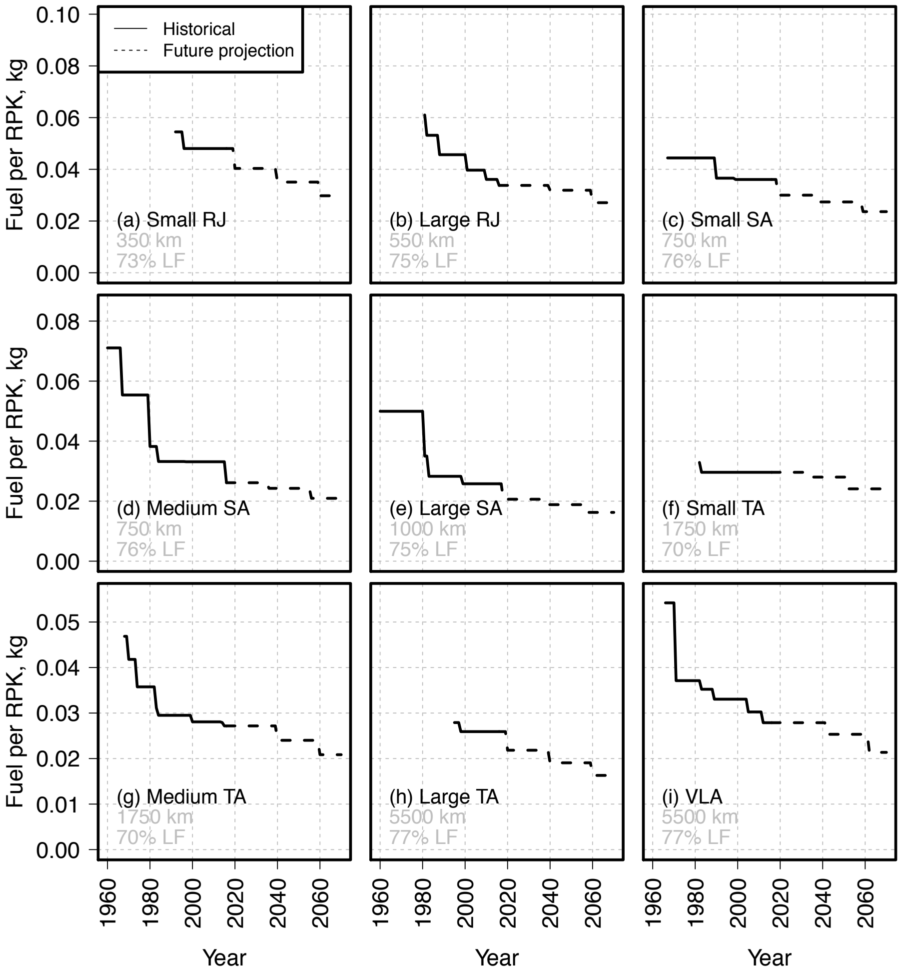
- Assessing emissions mitigation policy requires assessment of the measures that are available within-sector
  - CORSIA offsets emissions, but its impact will depend on fuel use, which depends on cost-effective fuel burn reduction mechanisms
  - Changes in technology will also affect aviation NOx, contrails, PM, noise etc.
- Start from Schäfer et al. (2016)
  - Marginal abatement costs for US narrowbody aircraft
  - Showed 2%/year cost-effective reduction in fuel use/RPK to 2050 is plausible
  - But fewer opportunities exist for other aircraft
- Extend analysis to other aircraft types and regions
- Use a global aviation systems model (AIM) to check how adoption would look in practice
  - Also assess how this changes with increasing carbon price

Types of within-sector mitigation measures

- Incremental updates to conventional technology
  - E.g A320neo, 737MAX
- Radical new technologies
  - E.g. CRP engines, blended wing body aircraft
- Retrofits
  - E.g. Re-engining, lightweighting
- Operational
  - E.g. CDM, optimised routing, reduced tankering
- Biofuels
  - Direct emissions may remain the same, reduction in fuel lifecycle emissions

Updates to conventional technology - 1

- Fuel/RPK will still decrease for conventional technology:
    - Fleet turnover removes older aircraft from the fleet
    - New aircraft becoming available (e.g. A320neo, A330neo, E-Jet E2, 737 MAX, 777-X...)
    - Further future improvements expected
        - More use of composites
        - Higher bypass ratio engines
        - Greater lift/drag



[Data: Piano-X (Lissys 2016); own projections]

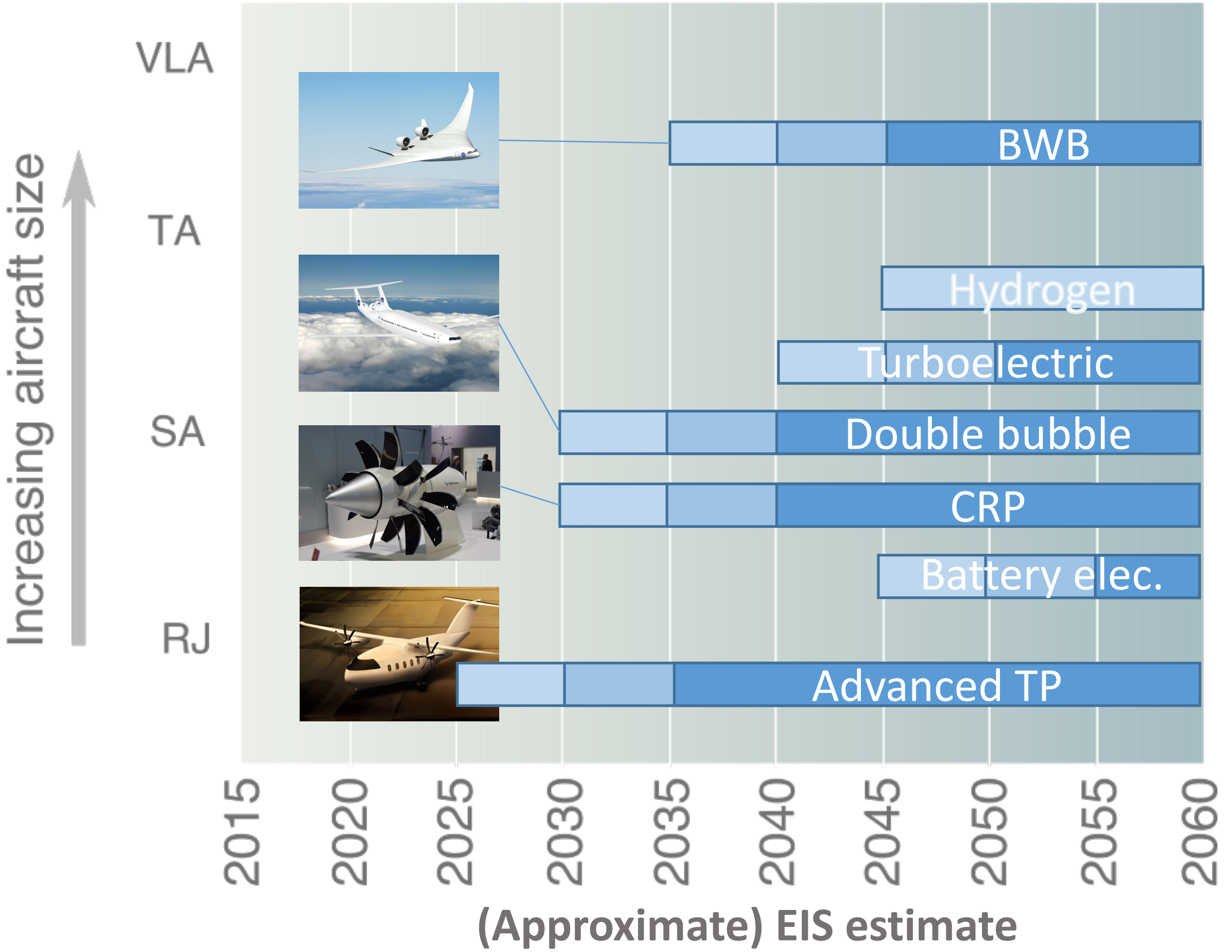
Updates to conventional technology - 2

- For this paper:
  - Assume published characteristics for next generation
  - For subsequent generations, 20 (15-25) year gap, 0.7 (0.5-1) %/year reduction in fuel burn

Technology	Size class	Available from	Capital cost, million US$(2015)	Change in non-fuel yearly cost, million US$ (2015)	Change in block fuel use, %	References
Next generation conventional	Small RJ	2020 (2018-2025)	40.9 (35.7-46.1)	-0.35 (- 0.3 - -0.47)	16 (15-21)	Embraer (2016); Al Zayat & Schäfer (2017); Airbus (2017); Schäfer et al. (2016); Vera-Morales et al. (2011); Leahy (2013); Reuters (2013); Airbus (2017)
	Large RJ	2020 (2018-2025)	53.6 (46.8-60.4)	-0.4 (-0.35 - -0.55)	16 (15-21)	
	Small SA	2019 (2018-2020)	69.6 (64.7-74.6)	-	20 (15 – 22)	
	Med SA	2016	75.8 (70.4-81.3)	-	20 (15 – 22	
	Large SA	2018 (2017-2019)	88.9 (82.5-95.2)	-	20 (15 – 22)	
	Small TA	No update; reference aircraft is already based on the 787-800				
	Med TA	2020 (2018-2022)	211 (189 – 233)	-0.026	12 (10 – 14)	
	Large TA	2020 (2018-2022)	251 (233-270)	-0.35 (0 – 0.07)	21 (17.5 – 23.7)	
	VLA	2020 (2017-2022)	305 (284-323)	-0.2 (0 – 0.4)	4	
Subsequent generation conventional	Small RJ	2040 (2033-2050)	41 (36-46)	-0.35 (- 0.3 - -0.47)	28 (25 – 32)	
	Large RJ	2040 (2033-2050)	54 (47-60)	-0.4 (-0.35 - -0.55)	28 (25 – 32)	
	Small SA	2039 (2031-2045)	75 (68 – 82)	-	30 (26 – 34)	
	Med SA	2036 (2031-2041)	83 (75 – 90)	-	30 (26 – 34)	
	Large SA	2038 (2032-2044)	97 (87 – 106)	-	30 (26 – 34)	
	Small TA	2032 (2027-2037)	123 (114 – 132)	-	14 (12 – 14)	
	Med TA	2040 (2033-2047)	211 (188 – 233)	-0.026	24 (22 – 24)	
	Large TA	2040 (2032-2047)	251 (233 – 270	-0.35 (0 – 0.07)	31 (29 – 33)	
	VLA	2042 (2039-2045)	306 (284 – 324)	-0.2 (0 – 0.4)	17 (15 – 17)	

Alternative technologies - 1

- Potentially upcoming aircraft technologies include:
  - Contra-rotating propellor engines (CRP)
  - Blended wing body (BWB) aircraft
  - NASA N+3 designs (including double bubble)
  - Battery and/or turboelectric aircraft
  - Hydrogen fuelled aircraft
  - Advanced/optimised turboprop designs
- Characteristics and timeline uncertain



[Images: NASA; Wikimedia commons]

Alternative technologies - 2

- For this paper:
  - Concentrate on relatively well-established designs:
    - Cost estimates available
    - Would require little/no adjustment to current infrastructure
    - Assume global availability, aircraft choice based on cost only
  - Excludes: NASA N+3, battery electric/turboelectric designs, hydrogen aircraft, next generation supersonic etc.

Technology	Size class	Available from	Capital cost, million US$(2015)	Change in non-fuel yearly cost, million US$ (2015)	Change in block fuel use, %	References
Advanced Turboprop	Small RJ	2030 (2025-2035)	22 (19 – 24)	1.7 (0.9 – 2.6)	43 (37 – 46)	Vera-Morales et al. (2011); Liebeck (2004); Schäfer et al. (2016)
	Large RJ	2030 (2025-2035)	28 (24 – 31)	1.7 (0.9 – 2.6)	43 (37 – 46)	
Optimised CRP	Small SA	2035 (2030-2040)	73 (61 – 85)	0.4 (0.2 – 0.5)	41 (40 – 45)	
	Med SA	2035 (2030-2040)	98 (82 – 115)	0.4 (0.2 – 0.6)	41 (40 – 45)	
	Large SA	2035 (2030-2040)	99 (83 – 116)	0.4 (0.2 – 0.6)	41 (40 – 45)	
Blended-Wing Body	Small TA	2040 (2035-2045)	217 (180 – 289)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	
	Med TA	2040 (2035-2045)	233 (194 – 310)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	
	Large TA	2040 (2035-2045)	249 (207 – 332)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	
	VLA	2040 (2035-2045)	364 (303 – 485)	-0.3 (-0.2 - -0.5)	30 (15 – 40)	

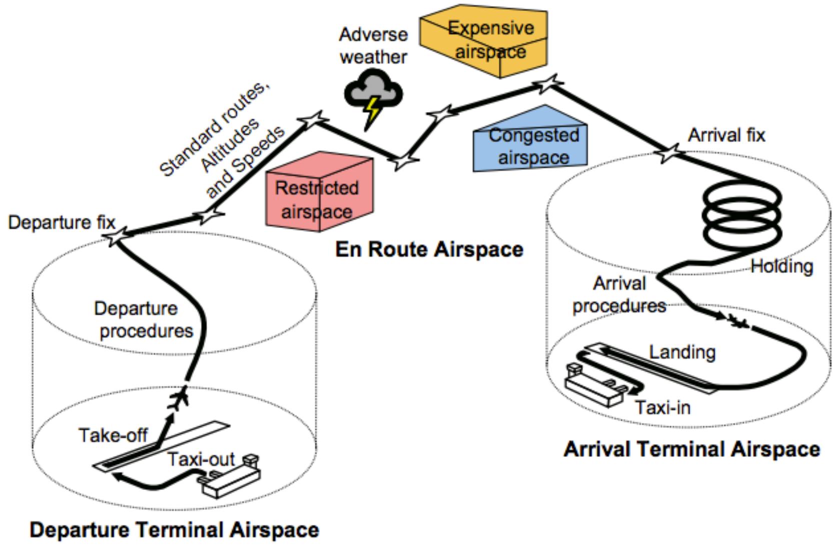
Retrofits

- Can be applied to existing aircraft, so uptake does not depend on fleet turnover
  - Some may be applicable only at D-check
  - Many are applicable to only part of the fleet, e.g. aircraft without winglets or with older engines

Technology	Size class	Available from	Capital cost, million US$(2015)	Change in non-fuel yearly cost, million US$ (2015)	Change in fuel use, %	References
Blended winglets	Small SA – Med TA	2015	0.85 – 1.9	-	3 (2 – 4)	Schäfer et al. (2016); Morris et al. (2009)
Surface Polish	Small RJ – Med TA	2015	0.03 – 0.13	0.03 – 0.16	1 (0.5 – 1.5)	
Carbon Brakes	Small RJ – VLA	2015	-	0.015 – 0.045	0.15 (0.1 – 0.2)	
Engine Upgrade Kit	Small RJ – Med TA	2015	0.5 – 1.8	-	1 (0.5 – 1.5)	
Re-engining	Small RJ – Med TA	2015	7.1 – 16.6	-	12.5 (10 – 15)	
Electric Taxi	Small RJ – VLA	2018	0.3 – 4	-	2.8 (1.8 -3.8)	
Cabin Weight Reduction	Small RJ – VLA	2015	0.2 – 2.3	-	1.2 (1.2 – 2.1)	

Operational measures - 1

- Strategies to reduce routing inefficiency and/or airport congestion
- Many options, e.g. CDAs, CDM, route optimization
- We group measures into bundles as in Marais et al. (2013)



Measure	Size class	Available from	Cost, million US$(2015)	Change in fuel use, %, for affected flight phase	References
Surface congestion management	Small RJ – VLA	2015	0.015 – 0.06	15 (10 – 20)	Marais et al. (2013); Schäfer et al. (2016)
Single engine taxi	Small RJ – VLA	2015	0 – 0.06	30 (20 – 40)	
Optimize departures	Small RJ – VLA	2015	0.2 – 0.6	20 (10 – 30)	
Reduce cruise inefficiency	Small RJ – VLA	2015	0.07 – 0.13	5.5 (2.8 – 8)	
Optimize approach	Small RJ – VLA	2015	0.2 – 0.6	40 (15 – 50)	

Operational measures - 2

- Can also consider changes in airline behaviour, e.g.
  - Tankering and/or using fuel reserves above the minimum required
  - Maintenance interval
  - Changes in frequency, load factor or aircraft type use
  - Will (probably) be adopted if/when cost-effective, but costs may be difficult to estimate

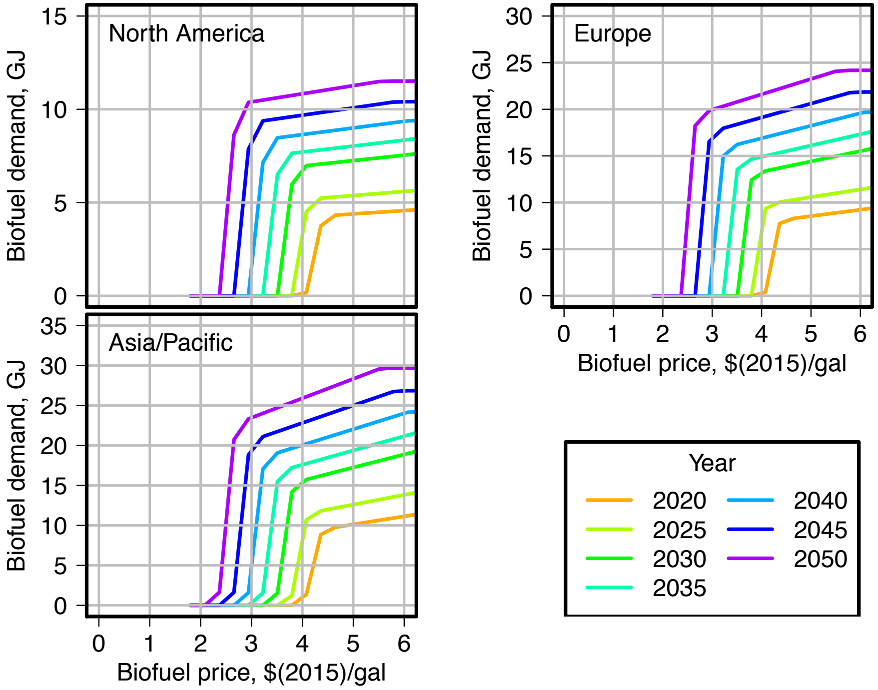
Measure	Size class	Available from	Cost, million US$(2015)	Change in fuel use, %	References
Reduced fuel reserves	Small RJ – VLA	2015	0 – 0.5	0.01 – 0.4	Schäfer et al. (2016); Morris et al. (2009); Henderson (2005)
Reduced tankering	Small RJ – Large SA	2015	0	0.26 (0.34 – 0.27)	
Increased engine maintenance	Small RJ – VLA	2015	0.001 – 0.002	2.4 (1 – 4)	
Increased aerodynamic maintenance	Small RJ – VLA	2015	0.001 – 0.002	1 (0.2 – 1.5)	
Engine wash	Small RJ – VLA	2015	-0.1 – 0.09	0.75 (0.25 – 1)	
Increased LF / reduced frequency	Small RJ – Large SA	2015	0.2 – 7.6	0	
Increased turboprop use	Small RJ – Large RJ	2015	2.6	30 (25 – 32)	

Alternative fuels - 1

- Many different options (e.g. Hileman & Stratton 2014)
    - Fuels requiring changes in aircraft design (e.g. hydrogen) would need a long time to percolate into the fleet
    - Drop-in fuel (e.g. F-T biomass fuels) uptake can be faster, but limited by infrastructure, supply, certification requirements
    - Many feedstock options, e.g. algae, cellulosic biomass
- Drop-in biofuels have already been trialled, but no widespread use
- Aviation biofuel supply will depend on the amount of biomass used by other sectors
    - Potential for double-counting emissions reductions
    - E.g. many future scenarios assume biomass is used in power generation

Alternative fuels - 2

- In this paper:
  - Assume a drop-in cellulosic biomass fuel
    - Relatively low projected costs, lower uncertainty than algae fuels
    - Does not compete with food production
  - Cost depends on demand
    - Use Hoogwijk et al. (2009) / Searle & Malins (2014) / DoE (2011) to generate biomass cost curve scenarios
    - Plant and transport costs assumed to add \$3.6/gal in 2020, falling to \$1.8 (1.3 – 2.3)/gal in 2050
    - Priority access for aviation assumed, but also run without biofuels

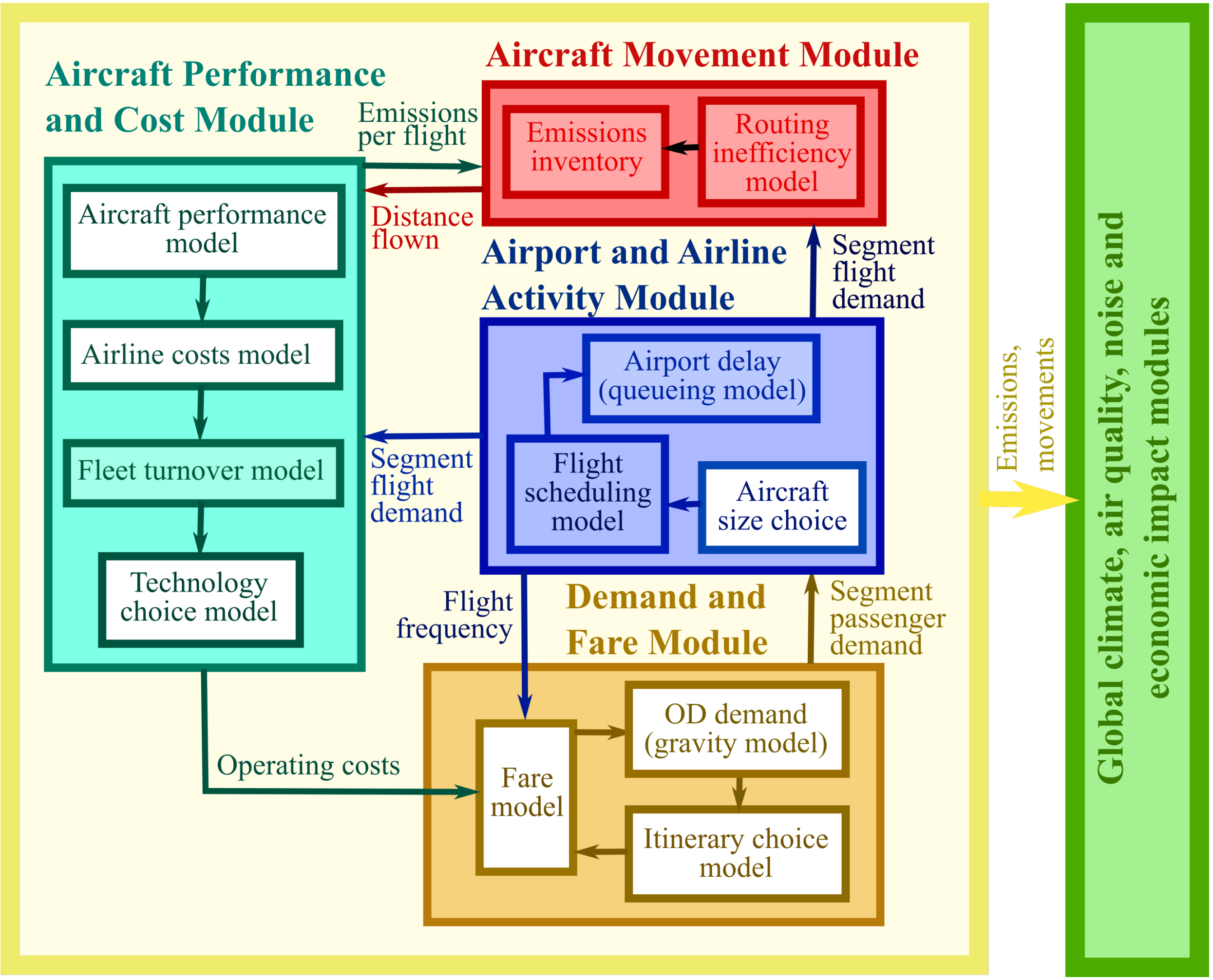


Integrated Modelling

- To estimate the achievable benefits from these measures we need to estimate:
    - Uptake by airlines in different future conditions
        - Requires model of fleet and fleet turnover
        - Uptake criteria (e.g. NPV with 10% discount rate)
        - Model of early/late adopters (Kar et al. 2009)
    - Any interactions between measures
    - The magnitude of feedback effects
        - E.g. better technology lowers costs, airlines reduce fares, demand increases, emissions go up
        - Early adoption of one measure affects later adoption of another measure
- To account for these effects we use a global aviation systems model (AIM)

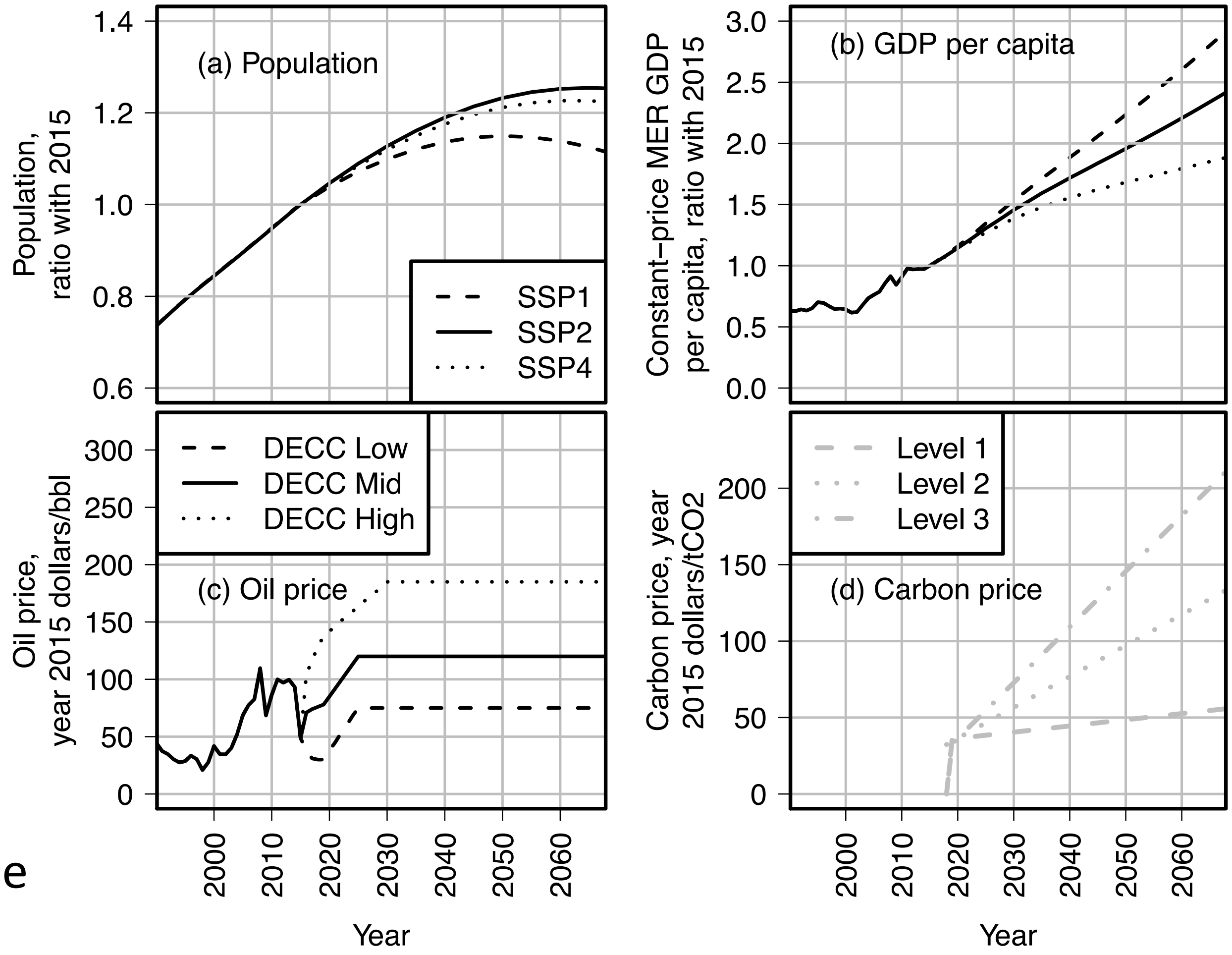
Aviation Integrated Modelling (AIM)

- Global, open-source aviation systems model
- Recently updated to 2015 base year
- See Dray et al. (2017) for validation study



Future scenarios

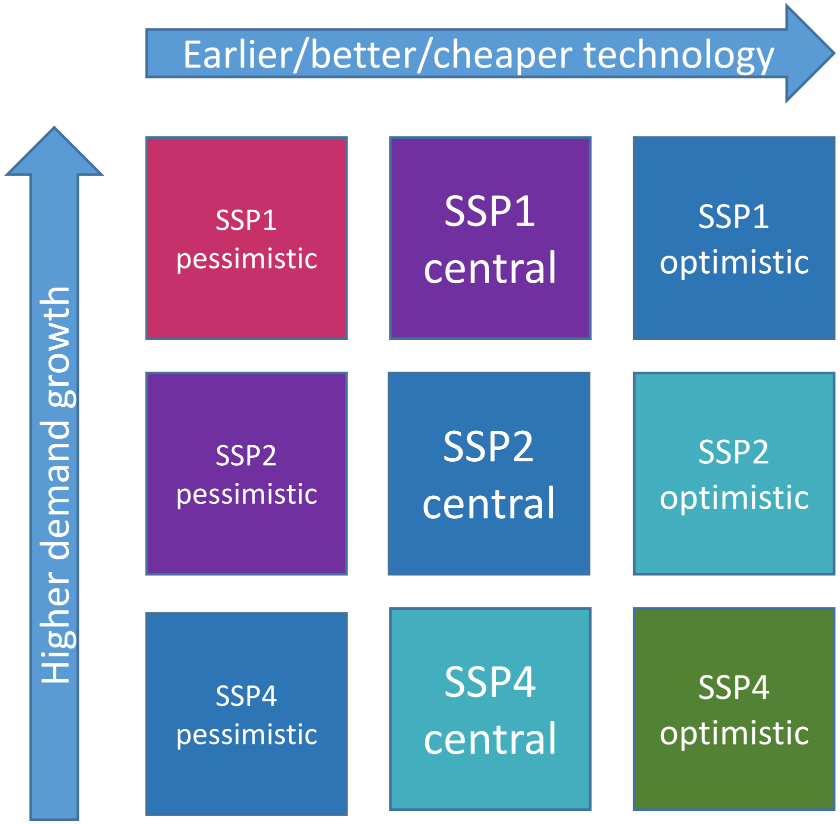
- Need projections of:
    - Population
    - GDP/capita
    - Oil price
    - Carbon price
- Use IPCC SSP scenarios
- Base case no carbon price
    - Use as a sensitivity variable



[Data: O'Neill et al., 2013; DECC, 2015]

Model uncertainty

- Many sources of uncertainty
- We are most interested in:
  - ❑ Uncertainty in demand
    - Run three scenarios for GDP/population/fuel price
  - ❑ Uncertainty in technology characteristics
    - Run three lenses
    - E.g. central case uses most likely estimates
    - Optimistic case assumes early availability, low cost and fuel use
    - Pessimistic case late availability, etc.



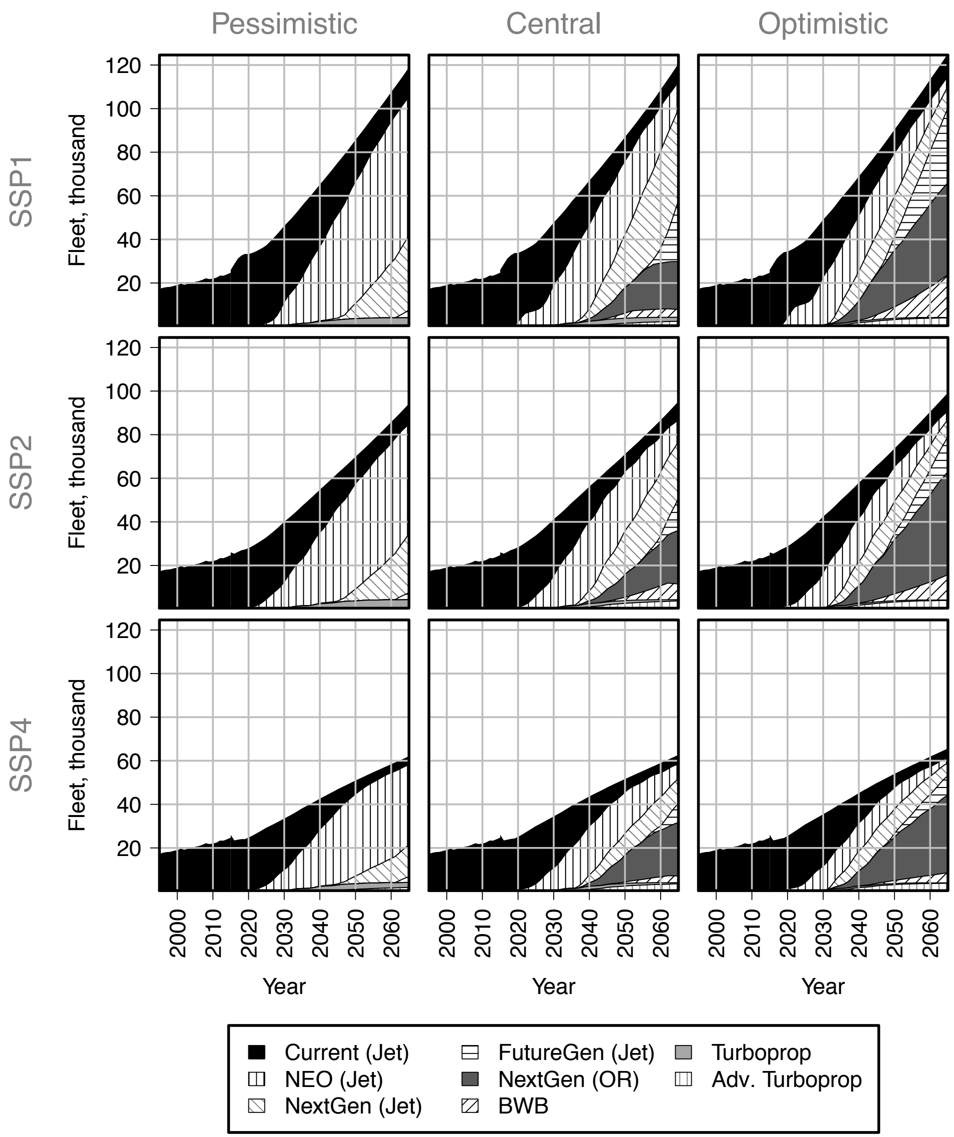
Earlier/better/cheaper technology

Higher demand growth

SSP1 pessimistic	SSP1 central	SSP1 optimistic
SSP2 pessimistic	SSP2 central	SSP2 optimistic
SSP4 pessimistic	SSP4 central	SSP4 optimistic

Future projections - 1

- RPK growth of 3.0 – 5.5%/year 2015-2035 by scenario
  - Mainly due to different GDP and fuel price projections
  - Technology scenario +/- 0.1%/year
  - Central SSP2 scenario grows at 4.4%/year to 2036
  - Comparable to Airbus (2016), Boeing (2016) 4.5 and 4.8%/year, next twenty years
- Uncertainty in technology characteristics has a large impact on fleet composition
- Relatively small differences with/without biofuel

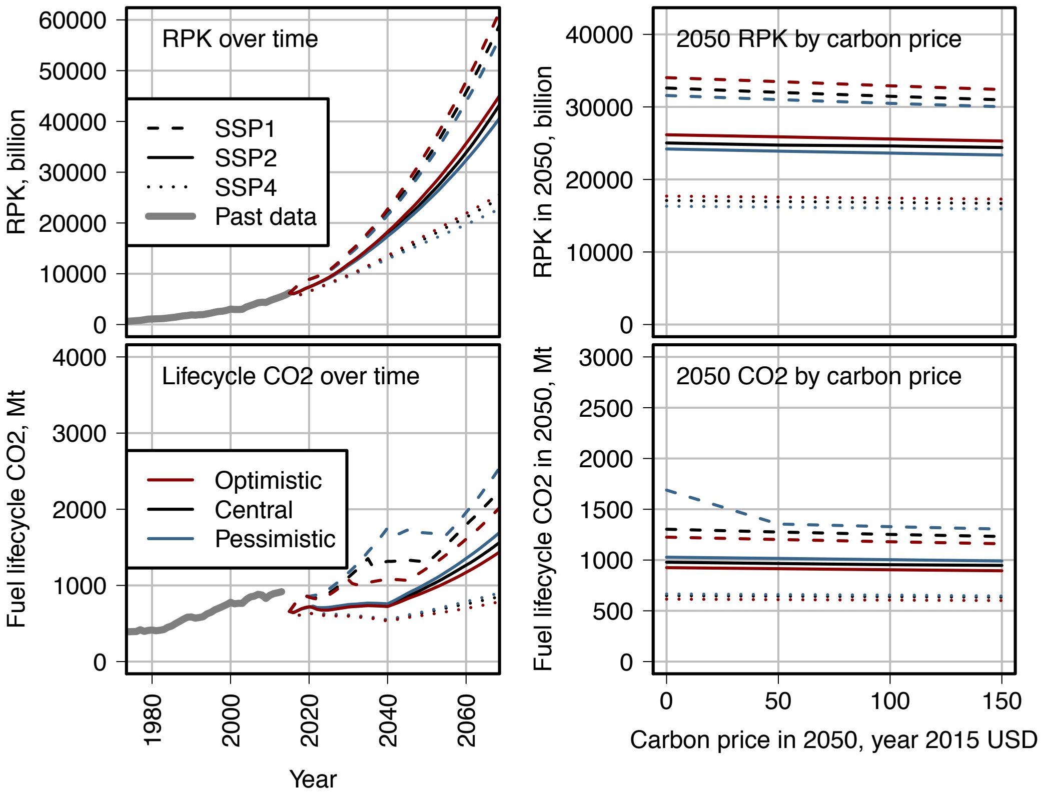


[Past data: FlightGlobal, 2016]

Future projections - 2

- 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]

Future projections - 2

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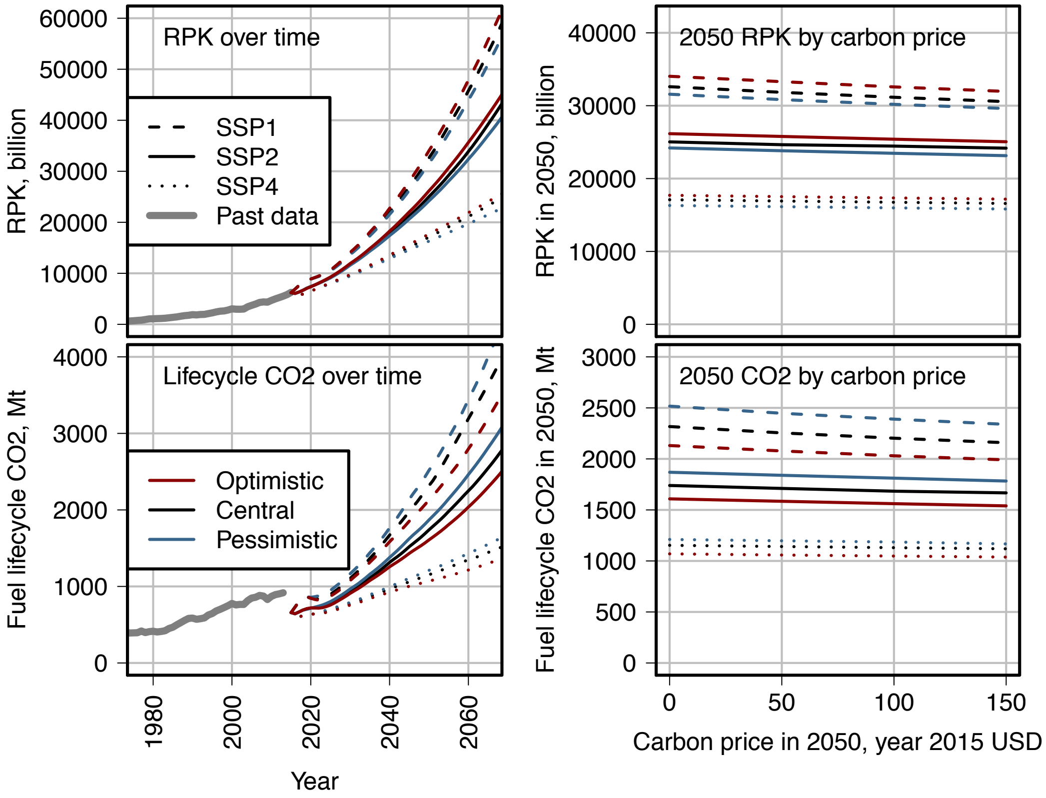
Without biofuels



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

Conclusions

- There are significant emissions reduction opportunities within the aviation sector
  - ❑ Cost-effective reductions of 1.9 – 3.0% per year in fuel lifecycle CO_2/RPK to 2050 possible, depending on fuel price and technology characteristics
  - ❑ About half of this is biofuel-dependent
    - ▪ 0.8 – 1.6 %/year with no biofuel at all
    - ▪ Outcomes sensitive to biofuel availability and price scenario
- Absolute emissions still go up to 2050 in all scenarios
  - ❑ However, GDP scenario has a large impact on total RPK, CO_2
- Likely within-sector impact of CORSIA at projected carbon prices is small (at least initially)

Extra slides

Future projections – Contribution by type

- Influence of different measures depends on timescale
    - Initial benefits from operational measures and retrofits which can be applied quickly
    - Technology impact is slower as it depends on fleet turnover
    - Biofuel uptake depends on development of production and distribution capacity
- Applying a carbon price does not have much effect on relative contribution
    - Slightly increases contribution of alternative technology in no-biofuels case