Evaluating Potential Measures to Reduce Aviation Fuel Consumption and Carbon Emissions

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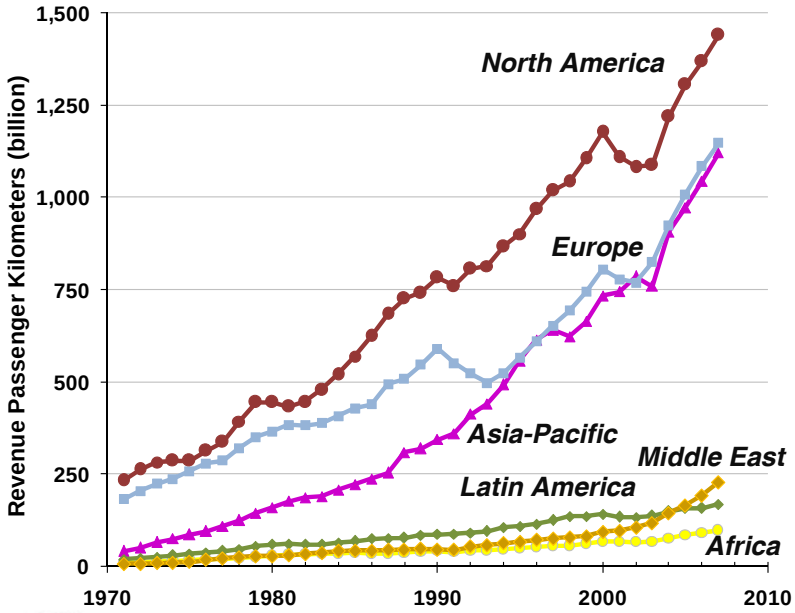
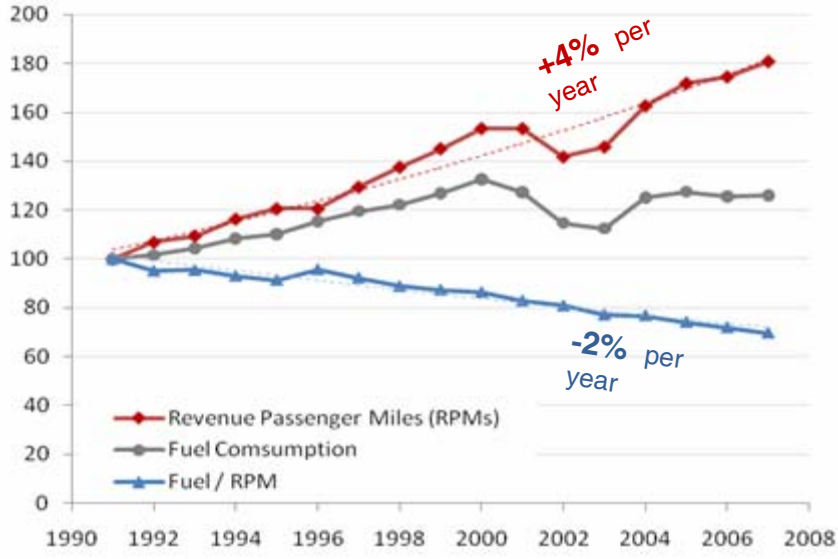
MIT Global Airline Industry Program - Industry Advisory Board Meeting
Massachusetts Institute of Technology
Nov. 6th 2008

Motivation

- **Increasing demand for air transportation worldwide**
- **Efficiency improvements evolve at a slower rate than demand**
- **Net fuel consumption and GHG emissions likely to increase**
  - Current contribution of aviation to GHG emissions: 2%

    likely to increase to 5% ~ 15% by 2050 (IPCC)
- **Public and political pressure about climate change likely to impact the aviation industry**
  (e.g. Emission Trading Scheme in Europe)
- **Further improvements and the implementation of mitigating measures are necessary for the industry to become sustainable**





* Data sources: ICAO, IATA, DOT BTS T2 U.S. Air Carrier Traffic And Capacity Statistics by Aircraft Type

Research Approach

- **Identification of mitigating measures to reduce fuel consumption and CO_2 emissions**
  - Identify areas of improvement and mitigating measures (portfolio of measures),
  - Estimate efficiency improvements,
  - Estimate development time and diffusion time into the aviation industry,

- **Develop system dynamic model to:**
  - quantify overall impact of the mitigating measures,
  - identify measures with the greatest potential for improvements and strategies for accelerating ,

- **Policy analysis**
  - Determine economic incentives to accelerate development time and technology diffusion,

Key Levers Influencing Fuel Consumption and CO2 Emissions

- **Fuel Consumption:**

$$Total\ Fuel\ Consumed = \sum_{all\ flights} (W_{empty} + W_{payload}) * \left(e^{\frac{R}{V} * SFC * \frac{D}{L}} - 1\right)$$

$$Pax * \frac{Avail.Seats}{Pax} * \frac{n_{flights}}{Avail.Seats}$$

Distance (Flight range)

Propulsion (Specific Fuel Consumption)

Aircraft **Empty Weight**

Payload Weight

Aircraft **Speed**

Aerodynamics (Lift/Drag Ratio)

Demand (Passenger Traffic)

Average Load Factor (ALF)

Fleet mix (Average Aircraft Size)

- **CO2 Emissions:**

$$CO_2 emissions = \sum_{all\ types\ of\ fuels} Fuel_i\ Consumed * \frac{CO_2}{Gallons\ of\ fuel_i}$$

CO_2 content in unit volume of $fuel_i$

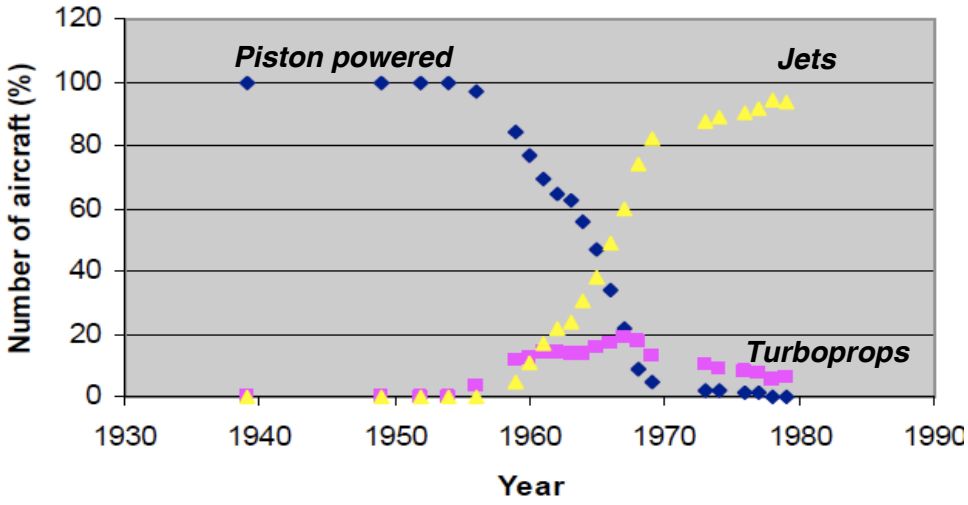
Categories of Mitigating Measures to Reduce Fuel Consumption & Emissions

Categories of Measures	Key Levers	Impact on Fuel Consumption	Impact on CO2 Emissions
Technology	- *Propulsion* - *Empty weight* - *Aerodynamics*	*Yes*	*Yes*
Operations	- *Propulsion* - *Empty weight* - *Payload weight* - *Aircraft speed* - *Distance*	*Yes*	*Yes*
Network & Rev. Management	- *Average Load Factor* - *Distance*	*Yes*	*Yes*
Fleet Management	- *Fleet Mix* - *Propulsion (Avg. SFC)*	*Yes*	*Yes*
Demand	- *Passengers (and cargo)*	*Yes*	*Yes*
Alternative Fuels	- *Energy input/sources*	*Limited*	*Yes*

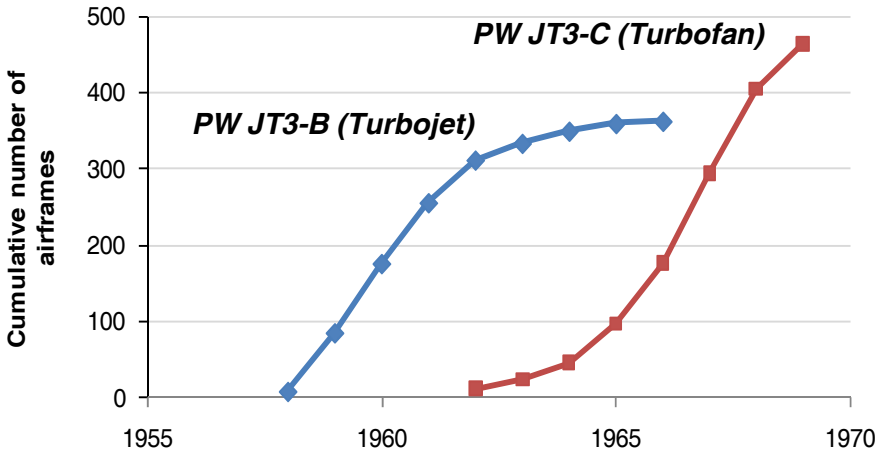
Dynamics of Change (i.e. Diffusion)

- **The impact of these mitigating measures will depend on the magnitude of the improvements and the diffusion of these technologies, procedures, practices into the system**

Introduction of the jet engine



Dynamics of diffusion of ***technology components*** *(e.g. engines)*



Time to replace 80% of the fleet: **15 years**
(Disruptive technology)

S-curve dynamics also identified for various generations of technology
(i.e. varying and time between generations)

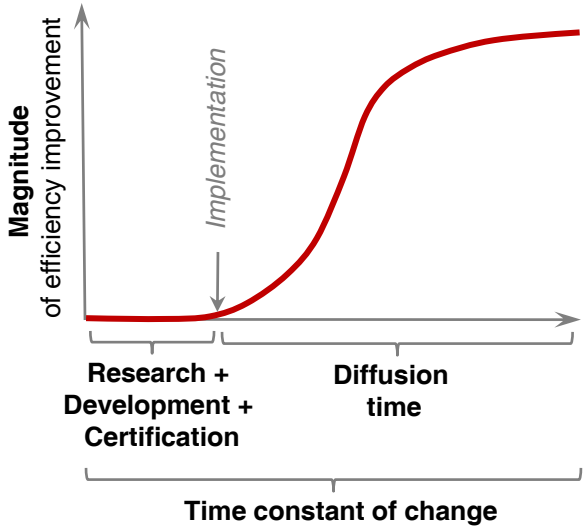
Note: Efficiency improvement between PW JT3-B and JT3-C: +30%

* Reference: NLR-CR-2005-669, "Fuel efficiency of commercial aircraft: An overview of historical and future trends", Peeters P.M.1, Middel J., Hoolhorst A

* Data source: Pratt & Whitney

Dynamics of Efficiency Improvement

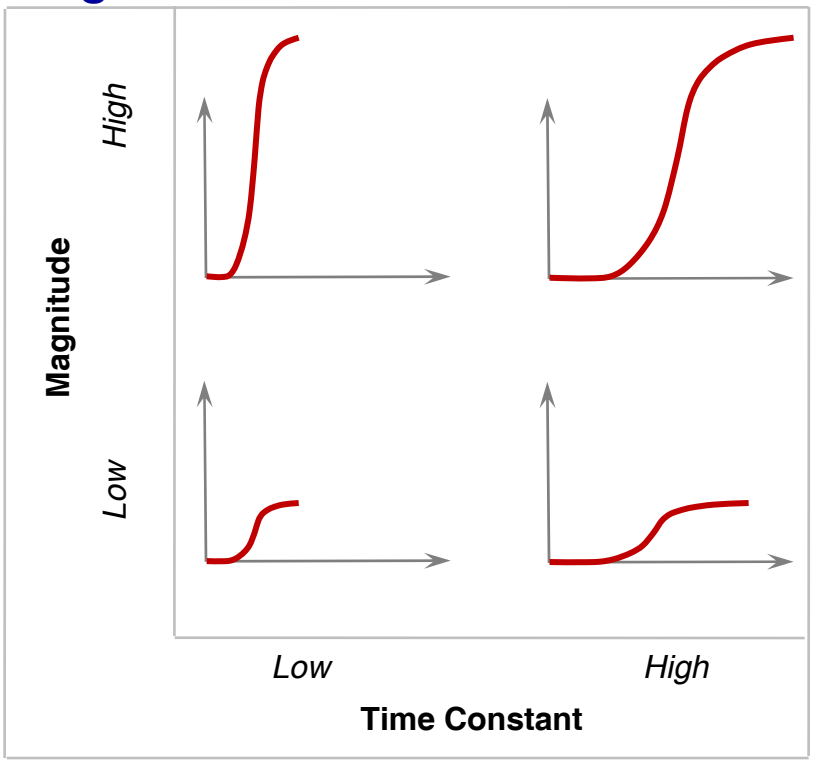
- **Implementation and diffusion of new technologies, procedures, operating schemes, result in S-curves efficiency improvements**

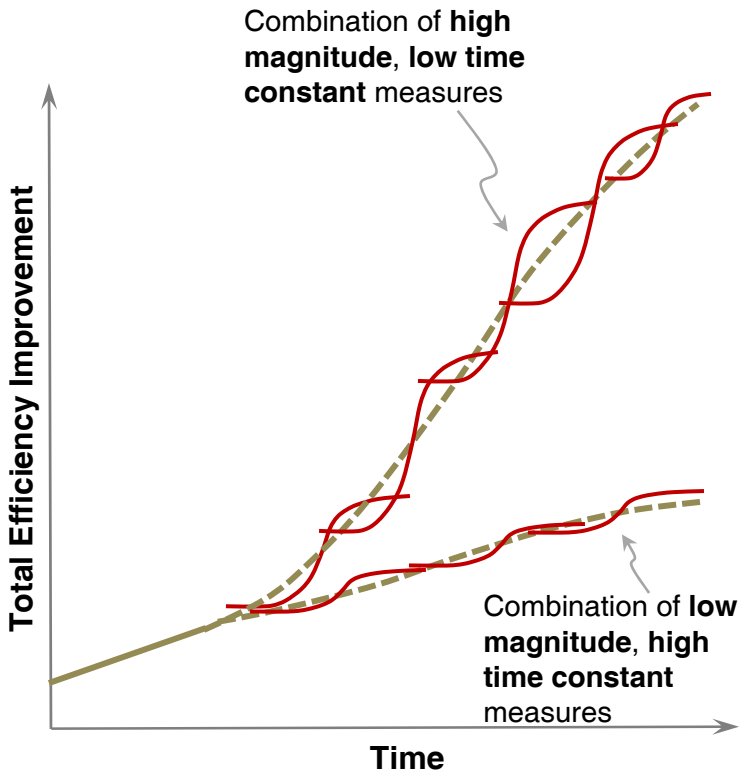


- **Magnitude of the efficiency improvement** depends on:
  - Magnitude of the improvement from the specific measure,
  - Fraction of the operation affected by the measure (e.g. ground vs. cruise),
  - Adoption rate (i.e. number of aircraft equipped in the fleet).
- **Time constant of the change** depends on:
  - Time to implementation = Research + Development + Certification
  - Diffusion time into the system (function of cost vs. benefits of the technology, procedures, practice, etc.),

Dynamics of Efficiency Improvement (cont.)

- **Individual sources of efficiency improvements** (i.e. measure) **are characterized by various magnitude and time constant**





- **How can a set of measures be combined to result in:**
  - High magnitude of total efficiency improvement,
  - and short time constant?

Mitigating Measures

- **Technology**
  - New Aircraft
    - *Improved propulsion & power supply systems*
      - ✓ *Use engines with higher By-Pass-Ratio (e.g. Open rotor, Geared turbofan),*
      - ✓ *Redesign combustors for improved fuel burn,*
      - ✓ *Use higher turbine inlet temperatures by utilizing advanced materials and coatings,*
      - ✓ *Improve 3D flow through the engines using 3D blades on compressor stages,*
      - ✓ *Replace APU's with fuel cells,*
      - ✓ *Others*
    - *Improved aerodynamics*
      - ✓ *Develop laminar flow wing profiles,*
      - ✓ *Develop non-planar wings (Winglets, Blended wings, Multiple wings, Box-wings, Joint wings,),*
      - ✓ *Develop active wings,*
      - ✓ *Develop laminar surfaces using coatings and paintings,*
      - ✓ *Design nacelles with laminar profiles and reduce drag,*
      - ✓ *Use shock wave/boundary layer devices (like micro-vortex generators) to reduce stagnation pressure loss,*
      - ✓ *Use riblets,*
      - ✓ *Use wings with variable camber,*
      - ✓ *Design laminar vertical and horizontal tail plane,*
      - ✓ *Reduce area of tail plane,*
      - ✓ *Develop laminar flow suction systems for wing, fuselage, stabilizers and nacelles,*
      - ✓ *Utilize slotted cruise airfoils,*
      - ✓ *Others*

$$Total\ Fuel\ Consumed = \sum_{all\ flights} (W_{empty} + W_{payload}) * \left(e^{\frac{R}{V} * SFC * \frac{D}{L}} - 1\right)$$

Mitigating Measures

- **Technology**
  - New Aircraft
    - *Reduce Aircraft Empty Weight*
      - ✓ *Use lightweight material for primary structures (e.g. composites for construction),*
      - ✓ *Use lightweight alloys on secondary load bearing structures,*
      - ✓ *Use lighter cabin seats,*
      - ✓ *Remove passive interior noise treatment(wall bags, environment control ducts) by active noise control technology,*
      - ✓ *Reduce number paint coats and weight,*
      - ✓ *Make lavatories out of composite material,*
      - ✓ *Implement fly by wire, fly by light technologies,*
      - ✓ *Use data bus for electrical systems,*
      - ✓ *Integrate avionics - merge multiple systems,*
      - ✓ *Use electric systems to replace hydraulics – like electric braking systems,*
      - ✓ *Use composite wiring and connectors,*
      - ✓ *Others.*

$$Total\ Fuel\ Consumed = \sum_{all\ flights} (W_{empty} + W_{payload}) * \left(e^{\frac{R}{V} * SFC * \frac{D}{L}} - 1\right)$$

Mitigating Measures

- **Technology**

$$Total\ Fuel\ Consumed = \sum_{all\ flights} (W_{empty} + W_{payload}) * \left(e^{\frac{R}{V} * SFC * \frac{D}{L}} - 1\right)$$

  - Retrofit Existing Aircraft
    - *Improve propulsion & power supply systems*
      - ✓ *Replace existing engines with new generation of engines*
      - ✓ *Upgrade core with 3D compressor blades, vanes and shrouds*
      - ✓ *Replace APU's with fuel cells.*
      - ✓ *Others*
    - *Improve aerodynamics*
      - ✓ *Use winglets/wingtip devices,*
      - ✓ *Use riblets,*
      - ✓ *Apply surface coatings to reduce skin-friction drag*
      - ✓ *Others*
    - *Reduce empty weight and payload*
      - ✓ *Use lighter cabin seats,*
      - ✓ *Remove passive interior noise treatment(wall bags, environment control ducts) by active noise control technology*
      - ✓ *Replace avionics,*
      - ✓ *Reconfigure airplane interior (e.g. remove galleys).*

Mitigating Measures

- **Operations**

$$Total\ Fuel\ Consumed = \sum_{all\ flights} (W_{empty} + W_{payload}) * \left(e^{\frac{R}{V} * SFC * \frac{D}{L}} - 1\right)$$

  - Reduce Empty Weight and Payload,
    - ✓ *Use light weight cargo containers,*
    - ✓ *Limit/Change fuel ferrying practices,*
    - ✓ *Limit/charge for number and weight baggage,*
    - ✓ *Reduce food onboard,*
    - ✓ *Limited carriage of extra potable water,*
    - ✓ *Transition from paper manuals to electronic freight bags (EFBs),*
    - ✓ *Remove on-board passenger service equipment (e.g. pillows, covers, etc.)*
    - ✓ *Reduce /eliminate duty free goods,*
    - ✓ *Others,*
  - Improve Aerodynamics & Performance,
    - ✓ *Minimize trim drag by optimizing C.G. location (i.e. cahnge location of equipment/luggage)*
    - ✓ *Sequence fuel burn between tanks,*
    - ✓ *Others,*
  - Improve Ground Operations,
    - ✓ *Single engine taxi,*
    - ✓ *Implement controlled push back,*
    - ✓ *Optimize ground paths,*
    - ✓ *Use tow-tugs instead of engine power for taxing,*
    - ✓ *Use fixed electric ground power instead of APU,*
    - ✓ *Use starting grids,*
    - ✓ *Others*

Mitigating Measures

- **Operations**
  - Flight Operations
    - ✓ *Optimize climb/descent paths,*
    - ✓ *Reduce lateral deviation from shortest route,*
    - ✓ *Operate at optimum cruise level,*
    - ✓ *Reduce cruise speed,*
    - ✓ *Conduct formation flying,*
    - ✓ *Conduct mid-air refueling for long flights,*
    - ✓ *Use holding and sequencing tools,*
    - ✓ *Perform continuous descent approaches (CDA),*
    - ✓ *Others.*

$$Total\ Fuel\ Consumed = \sum_{all\ flights} (W_{empty} + W_{payload}) * \left(e^{\frac{R}{V} * SFC * \frac{D}{L}} - 1\right)$$

- **Alternative Fuels**
  - Aircraft fuel
    - ✓ *Petroleum based fuels (e.g. Gasoline, Diesel, Compressed Natural Gas, etc.)*
    - ✓ *Biofuels (1st generation: corn, etc., 2nd generation: Palm Oil, Cellulosic, 3rd generation: Algae)*
    - ✓ *Hydrogen,*
    - ✓ *Others,*
  - Energy sources for ground equipment (e.g. tugs)
    - ✓ *Petroleum based fuels (e.g. Gasoline, Diesel, Compressed Natural Gas, etc.)*
    - ✓ *Electric,*
    - ✓ *Biofuel,*
    - ✓ *Hydrogen,*
    - ✓ *Others*

$$CO_2 emissions = \sum_{all\ types\ of\ fuels} Fuel_i\ Consumed * \frac{CO_2}{Gallons\ of\ fuel_i}$$

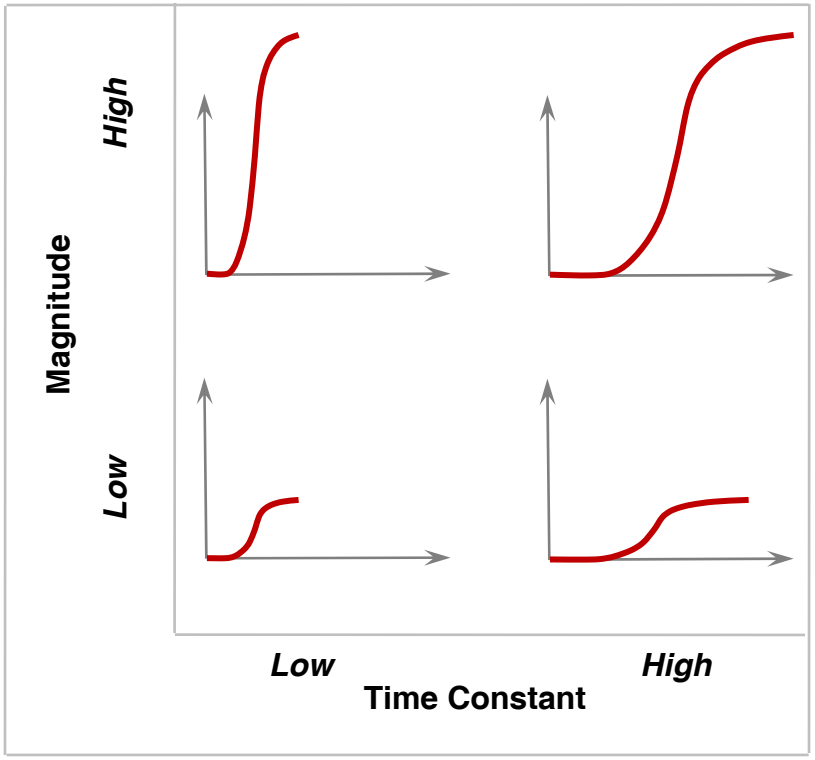
Mitigating Measures

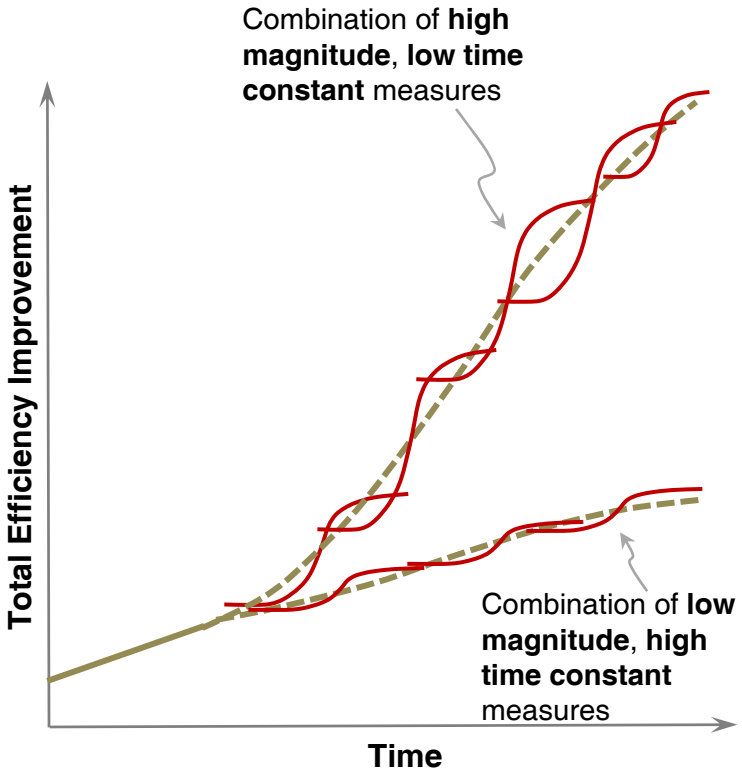
$$Total\ Fuel\ Consumed = \sum_{all\ flights} (W_{empty} + W_{payload}) * \left(\frac{R}{eV} * SFC * \frac{D}{L} - 1\right) * Pax * \frac{Avail.Seats}{Pax} * \frac{n_{flights}}{Avail.Seats}$$

- **Airline Network & Revenue Management**
  - ✓ *Increase load factor,*
  - ✓ *Break long haul flights into several short haul flights,*
  - ✓ *Choose and operate at less congested airports,*
  - ✓ *Others.*
- **Airline Fleet Management**
  - ✓ *Change fleet mix to impact aircraft size,*
  - ✓ *Park older aircraft,*
  - ✓ *Others.*
- **Impacting Passenger Demand through Policies**
  - ✓ *Charge for CO_2 emissions (e.g. Emission Trading Scheme),*
  - ✓ *Increase taxes on petroleum based fuels,*
  - ✓ *Others.*

Dynamics of Efficiency Improvements

- **Individual sources of efficiency improvements characterized by various magnitude and time constant**





Preliminary Evaluation of the Magnitude of Improvements and Diffusion Time

Categories of Mitigating Measures		Mitigating Measures	Magnitude of Fuel Efficiency Improvement	Diffusion Time
Technology	New aircraft	*Next generation of aircraft*	20%	Long
		Blended wing body	20-25%	40+ yrs
	Retrofit existing aircraft	*Retrofit engines on existing aircraft*	10-15%	Medium
	Aerodynamics	*Winglets/Riblets*	< 5%	< 5 yrs
	Weight Reduction	*Lighter materials for airframe*	6-10%	Long
		Retrofit aircraft interior (e.g. light weight seats)	Low	Medium
Operations	Flight operations	*Reduce cruise speed*	3 - 5%	Short
		Reduce vertical seperation	1 - 2%	Medium
		Reduce lateral deviation from shortest route	5 - 8%	Long
		Continous Descent Approach (CDA)	2%	Medium
	Ground operations	*Single engine taxi*	1%	Short
		Optimized ground path	1 - 2%	Medium
		Reduce weight by onboard service equipment	< 1%	< 1yr
	Propulsion	*Engine washing*	1%	3 -5 yrs
Network & Fleet Management		*Change scheduling/fleet composition*	Medium	Long
		Operate at less congested airports & reduce congestion	Medium	Medium
Alternative Fuels		*Transition to Alternative Fuels (e.g.biofuels)***	High	Medium

Legend

Magnitude of Fuel Efficiency Improvement		Diffusion Time	
High	>10%	Long	>10 yrs
Medium	5-10%	Medium	5-10 yrs
Low	<5%	Short	2-5 yrs

*** Note: Improvements in GHG emissions only. No/Limited effects on fuel efficiency.*

Conclusions & Future Work

- **Identified a broad set of mitigating measures to reduce fuel consumption and CO2 emissions** *-> Looking for feedback and input*

- **The greatest improvements in fuel consumptions and CO_2 emissions will be achieved through the implementation of mitigating measures with:**
  - high magnitude improvements,
  - short implementation and diffusion time,

- **Future work will focus on;**
  - evaluating the magnitude of efficiency improvements and development and diffusion time for the broad set of measures,
  - Identifying mechanisms and policies that can accelerate the development and diffusion time into the system.

Questions
&
Feedback

Thank you !