Evaluating Potential Measures to Reduce Aviation Fuel Consumption and Carbon Emissions

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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 CO₂ 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:

\[
Total \ Fuel \ Consumed = \sum_{all \ flights} \left( W_{\text{empty}} + W_{\text{payload}} \right) \times \left( \frac{R}{\text{eV}} \times \frac{\text{SFC}}{\text{D/L}} - 1 \right)
\]

- **Demand** (Passenger Traffic)
- **Average Load Factor** (ALF)
- **Fleet mix** (Average Aircraft Size)
- **Aircraft Empty Weight**
- **Payload Weight**
- **Aircraft Speed**
- **Aerodynamics** (Lift/Drag Ratio)

### CO2 Emissions:

\[
CO_2 \ emissions = \sum_{all \ types \ of \ fuels} \text{Fuel}_i \ Consumed \times \frac{\text{CO}_2}{\text{Gallons \ of \ fuel}_i}
\]

- **CO\textsubscript{2}** content in unit volume of fuel\textsubscript{i}
### Categories of Mitigating Measures to Reduce Fuel Consumption & Emissions

<table>
<thead>
<tr>
<th>Categories of Measures</th>
<th>Key Levers</th>
<th>Impact on Fuel Consumption</th>
<th>Impact on CO2 Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>- Propulsion</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>- Empty weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Aerodynamics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations</td>
<td>- Propulsion</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>- Empty weight</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>- Payload weight</td>
<td>Yes</td>
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<td></td>
<td>- Aircraft speed</td>
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<td></td>
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<tr>
<td></td>
<td>- Distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Network &amp; Rev. Management</td>
<td>- Average Load Factor</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>- Distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fleet Management</td>
<td>- Fleet Mix</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>- Propulsion (Avg. SFC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand</td>
<td>- Passengers (and cargo)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternative Fuels</td>
<td>- Energy input/sources</td>
<td>Limited</td>
<td>Yes</td>
</tr>
</tbody>
</table>
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.

Dynamics of Change (i.e. Diffusion)

- Introduction of the jet engine

**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%


* Data source: Pratt & Whitney
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.),
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

\[
\text{Total Fuel Consumed} = \sum_{\text{all flights}} (W_{\text{empty}} + W_{\text{payload}}) \times \left( e^\frac{R}{eV \text{SFC}} \frac{D}{L} - 1 \right)
\]
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.

\[
Total \text{ Fuel Consumed} = \sum_{\text{all flights}} (W_{\text{empty}} + W_{\text{payload}}) \times \left( \frac{R}{e^V \times SFC} \times \frac{D}{L} - 1 \right)
\]
## Mitigating Measures

### Technology

- **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).

\[
Total \ Fuel \ Consumed = \sum_{\text{all flights}} (W_{\text{empty}} + W_{\text{payload}}) \times \left( \frac{R}{e^{V \text{SFC}}} \right) \left( \frac{\text{D}}{\text{L}} - 1 \right)
\]
Mitigating Measures

- **Operations**
  - 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. change 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

\[
Total \ Fuel \ Consumed = \sum_{all \ flights} (W_{\text{empty}} + W_{\text{payload}}) \times \left( \frac{R}{eV} \frac{S}{SFC} \frac{D}{D} - 1 \right)
\]
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.

- **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
Mitigating Measures

- **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 CO₂ emissions (e.g. Emission Trading Scheme),
  - Increase taxes on petroleum based fuels,
  - Others.

\[
\text{Total Fuel Consumed} = \sum_{\text{all flights}} (W_{\text{empty}} + W_{\text{payload}}) \times \left( \frac{P_{\text{f}}}{SFC} \frac{S}{D} - 1 \right)
\]
Dynamics of Efficiency Improvements

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

![Graph showing the dynamics of efficiency improvements with different combinations of magnitude and time constant.]

- Combination of high magnitude, low time constant measures
- Combination of low magnitude, high time constant measures
### Preliminary Evaluation of the Magnitude of Improvements and Diffusion Time

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

**Legend**

<table>
<thead>
<tr>
<th>Magnitude of Fuel Efficiency Improvement</th>
<th>Diffusion Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>&gt;10%</td>
</tr>
<tr>
<td>Medium</td>
<td>5-10%</td>
</tr>
<tr>
<td>Low</td>
<td>&lt;5%</td>
</tr>
<tr>
<td></td>
<td>Short</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
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<td></td>
<td>Long</td>
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<tr>
<td></td>
<td>&gt;10 yrs</td>
</tr>
<tr>
<td></td>
<td>5-10 yrs</td>
</tr>
<tr>
<td></td>
<td>Short</td>
</tr>
<tr>
<td></td>
<td>2-5 yrs</td>
</tr>
</tbody>
</table>

**Note:** Improvements in GHG emissions only. No/Limited effects on fuel efficiency.
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 CO2 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!