Aviation Fuels – drivers, impacts and benefits

05/03/2017

• Jon Hart
Global passenger traffic continues to expand

Since 2010, RPKs have mostly stayed above their long-term historical average.

Source: IATA, Rolls-Royce analysis
## Our 20 year global forecast

<table>
<thead>
<tr>
<th>World Fleet Forecast</th>
<th>2016</th>
<th>2035</th>
<th>CAGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP, real</td>
<td>76tn</td>
<td>132tn</td>
<td>2.9%</td>
</tr>
<tr>
<td>Population</td>
<td>7.4bn</td>
<td>8.8bn</td>
<td>0.9%</td>
</tr>
<tr>
<td>ASK</td>
<td>8.9tn</td>
<td>19.7tn</td>
<td>4.3%</td>
</tr>
<tr>
<td>RPK</td>
<td>6.9tn</td>
<td>16.2tn</td>
<td>4.6%</td>
</tr>
<tr>
<td><strong>Passenger Widebody Aircraft In Service</strong></td>
<td><strong>3,900</strong></td>
<td><strong>9,150</strong></td>
<td>4.6%</td>
</tr>
<tr>
<td><strong>Passenger Widebody Demand</strong></td>
<td></td>
<td>8,250</td>
<td></td>
</tr>
<tr>
<td><strong>Passenger Single Aisle Demand</strong></td>
<td></td>
<td>22,400</td>
<td></td>
</tr>
<tr>
<td><strong>60% Growth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>40% Replacement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Passenger aircraft > 110 seats; no freighters

RPK: Revenue Passenger Kilometres measures actual passenger traffic

ASK: Available Seat Kilometres measures available passenger capacity

CAGR: Compound Annual Growth Rate

Source: Oxford Economics global economic model, United Nations Population Division, Rolls-Royce analysis
Our Environment Strategy

Support customers by further reducing the environmental impact of our products and services

Develop new technology and capability for future low emission products and services

Continually reduce the environmental impact of all our business activities

Rolls-Royce proprietary information
The Environmental Challenge

Global
- **Climate change** (and fuel use)

Local
- **Local air quality**
  - NOx, CO & particulates
- **Noise**

Gas turbines, in the ‘use phase’, contribute over 99% of the climate change impact.

Source: World Resources Institute
## CAEP Standards - Recent and Future Regulations

<table>
<thead>
<tr>
<th>CAEP mtg</th>
<th>Standard agreed</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAEP8 2010</td>
<td>NOx (CAEP8) – amendment to Chapter 2 (subsonic emissions)</td>
<td>New Types 2014</td>
</tr>
<tr>
<td>CAEP9 2013</td>
<td>Airport Noise (Chapter 14 / Stage 5)</td>
<td>New Types Implementation 2017 (&gt;55t), 2020 (&lt;55t)</td>
</tr>
<tr>
<td>CAEP10 2016</td>
<td>CO₂ (first civil subsonic standard)</td>
<td>2020 New Types 2023/2028 Production</td>
</tr>
<tr>
<td></td>
<td>nvPM – LTO Transition Standard (Mass Concentration Limit)</td>
<td>New Types and in-Production 2020 All Pass Standard</td>
</tr>
<tr>
<td>(starting Feb 2016)</td>
<td>Independent Experts Review on NOx CO₂ and Noise</td>
<td>Timing likely 2017 and might feed into future NOx standard work.</td>
</tr>
<tr>
<td></td>
<td>Supersonics airport noise and emissions standards</td>
<td>Adopting subsonic noise/emissions standards in separate chapters. Earliest implementation 2023?</td>
</tr>
<tr>
<td>CAEP12 2022</td>
<td>Potential new engine NOx standards Sonic Boom Noise Standards</td>
<td>Earliest implementation 2026?</td>
</tr>
</tbody>
</table>
Environmental trades

Increase engine pressure ratio
- Low NOx combustor

Increase bypass ratio
- Lightweight CTi fan system and ENABLES
- Fully integrated slim-line nacelle

NOx

CO$_2$ (SFC)

CO$_2$ (Weight drag)

CO$_2$ (SFC)

Noise
Flightpath 2050 environmental goals

**CO₂ (Engine)**
- Trent 800
- Trent 500
- Trent 900
- Trent 1000
- Trent XWB

**NOx (Engine)**
- Trent 800
- Trent 500
- Trent 900
- Trent 1000
- Trent XWB

**Noise (Aircraft)**
- Trent 800 (Boeing 777)
- Trent 500 (Airbus A340)
- Trent XWB (Airbus A350XWB)

**ACARE goal -75% CO₂ overall reduction:**
- -30% Rolls-Royce contribution

**ACARE goal -90% NOx overall reduction:**
- -75% Rolls-Royce contribution
- -15% from operational efficiency improvements

**ACARE goal -65% aircraft noise reduction:**
- -45dB cumulative
- Operational improvements and aircraft design will give significant further reductions

- Trent family
- Technology demonstrator engine targets
- ACARE (Advisory Council for Aviation Research and Innovation in Europe) Flightpath 2050 target

Rolls-Royce proprietary information
We must optimise at aircraft level
Sustainable Aviation Infographic

SUSTAINABLE AVIATION CO₂ ROAD-MAP

1. Set vision

2. More efficient operations and airspace
   Improve efficiency of flights by 9% by 2050.

3. Introduce new aircraft
   UK airlines have already invested over £35 billion on 470 new aircraft since 2005 and have many more on order. These aircraft are at least 14% more fuel efficient than the aircraft they replace.

4. Design future aircraft
   Aerospace manufacturers are investing heavily in the cutting edge technology that will ensure the next generation of aircraft and engines will be able to reduce CO₂ emissions further.

5. Start the transition to sustainable aviation fuel
   Offers a 50% life cycle CO₂ saving compared to using fossil fuel.

6. Invest in global carbon markets
   Supporting a halving of global aviation’s net CO₂ emissions by 2050.

2010 START
Challenge - how to accommodate expected aviation demand growth within national and global climate change objectives

2050 FORECAST OPPORTUNITY
More than doubling UK aviation without a substantial increase in CO₂ emissions, Potential to halve net CO₂ emissions.

Sustainable Aviation, December 2012

Rolls-Royce
Manufacturing Technology Drivers

Market Drivers
- Fuel efficiency • up
- Weight • down
- Emissions • down
- Ownership Cost • down
- Reliability • up
- Time to market • down

New Product
- Advanced affordable materials
- Novel low part count geometry
- Fit for purpose specifications
- High perform durable products

Business Needs
- Cost base • down
- Safety • up
- Stability / Capability • up
- Responsiveness • up
- Capital exposure • down
- Globalisation • up

New Processes
- Fundamentally Capable
- Stable & Low Cost
- Flexible & Transferrable

New Factories
- Standard Template
- Low energy & low cost
- Future proofed

New Skills
- Flexible & cost conscious
- Higher capability baseline
- Technology & IT savvy

Rolls-Royce proprietary information
Manufacturing Technology Drivers – fuel parallels

Market Drivers
- Fuel efficiency - up
- Weight – down
- Emissions - down
- Ownership Cost – down
- Reliability - up
- Time to market – down

New Product
- Advanced affordable materials
- Novel low part count geometry
- Fit for purpose specifications
- High perform durable products

New Processes
- Fundamentally Capable
- Stable & Low Cost
- Flexible & Transferrable

New Factories
- Standard Template
- Low energy & low cost
- Future proofed

Business Needs
- Cost base – down
- Safety - up
- Stability / Capability - up
- Responsiveness – up
- Capital exposure - down
- Globalisation - up

New Skills
- Flexible & cost conscious
- Higher capability baseline
- Technology & IT savvy
Looking after the present – “drop”-in fuels

Certify New fuels

Re-Certify Every engine type in service

OR

ASTM

INTERNATIONAL

Standards Worldwide

Rolls-Royce

GE

Pratt & Whitney

Honeywell

Rolls-Royce proprietary information
Fuel is a multi-purpose fluid
Alternative Fuels

†Actively engaged approving sustainable novel drop-in fuels to enable wider use
Evaluating potential benefits for local air quality and emissions reduction

Advanced fuels offering emissions benefits for 2050

† To date, 5 alternative fuel processing routes have been cleared through ASTM -more in progress)
Fuel Specification and FFP testing

D7566 robust approval for alternative fuels

FT fuels D4054 / FFP testing
- Completed
- Proven feedstock agnostic

Assumes:
- fuel processing
- chemical composition
- characteristics
  all same as FFP testing samples

HRJ fuels FFP testing

Specification robust for all FT fuels

Specification robust for all HRJ fuels

Until product robustness demonstrated:
- Unique Specifications (separate Annexes) for each feedstock/process
## Fuel clearance status - 2016

<table>
<thead>
<tr>
<th>Year approved</th>
<th>Short name</th>
<th>Description</th>
<th>Max Blend ratio with JetA/A1</th>
<th>Approval details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990s</td>
<td>CtL FT-SPK</td>
<td>SASOL semi-synthetic Coal-To-Liquid Fischer-Tropsch Synthetic Paraffinic Kerosene</td>
<td>50%</td>
<td>Def Stan 91-91</td>
</tr>
<tr>
<td>2008</td>
<td>CtL FT-SPK</td>
<td>SASOL fully-synthetic Coal-To-Liquid Fischer-Tropsch Synthetic Paraffinic Kerosene</td>
<td>100%</td>
<td>Def Stan 91-91</td>
</tr>
<tr>
<td>2009</td>
<td>XtL FT-SPK</td>
<td>Generic XtL (Biomas/Gas/Coal to liquid) Fischer-Tropsch Synthetic Paraffinic Kerosene</td>
<td>50%</td>
<td>ASTM D7566 A1</td>
</tr>
<tr>
<td>2011</td>
<td>HEFA HVO</td>
<td>Hydrogenated Esters and Fatty Acids / Aka Hydrogenated Vegetable Oils</td>
<td>50%</td>
<td>ASTM D7566 A2</td>
</tr>
<tr>
<td>2014</td>
<td>SIP DSHC</td>
<td>Farnesane, SIP (synthesised iso-paraffins) aka DSHC, (Direct Sugar to Hydro Carbons),</td>
<td>10%</td>
<td>ASTM D7566 A3</td>
</tr>
<tr>
<td>2015</td>
<td>FT-SKA IPK/A</td>
<td>Fischer-Tropsch Synthetic Kerosene with Aromatics aka Iso Paraffinic Kerosene with Synthetic Aromatics</td>
<td>50%</td>
<td>ASTM D7566 A4</td>
</tr>
<tr>
<td>2016</td>
<td>AtJ - SPK</td>
<td>Alcohol (isobutanol) to Jet</td>
<td>30%</td>
<td>ASTM D7566 A5</td>
</tr>
</tbody>
</table>

Ideal fuel improvements for environmental benefits

Reduced climate impact
- Lower CO₂ emissions
  - Low fuel burn £ - now regulated
  - Better fuel energy density (higher calorific value)
  - Low life-cycle CO₂
  - Reduce Contrail formation (+/-) – aromatics / hydrogen vs particulates

Improved air quality:
- Lower/No Smoke/particulates
  - Non volatile particulate matter (nvPM) - regulated
  - Volatile particulate matter (vPM) -
- No aromatics – but impact on sealing
- No sulphur – but impact on lubricity
<table>
<thead>
<tr>
<th>CAEP mtg</th>
<th>Standard agreed</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAEP8 2010</td>
<td>NOx (CAEP8) – amendment to Chapter 2 (subsonic emissions)</td>
<td>New Types 2014</td>
</tr>
<tr>
<td>CAEP9 2013</td>
<td>Airport Noise (Chapter 14 / Stage 5)</td>
<td>New Types Implementation 2017 (&gt;55t), 2020 (&lt;55t)</td>
</tr>
<tr>
<td>CAEP10 2016</td>
<td>CO₂ (first civil subsonic standard)</td>
<td>2020 New Types 2023/2028 Production</td>
</tr>
<tr>
<td></td>
<td>nvPM – LTO Transition Standard (Mass Concentration Limit)</td>
<td>New Types and in-Production 2020 All Pass Standard</td>
</tr>
<tr>
<td></td>
<td>Independent Experts Review on NOx CO₂ and Noise</td>
<td>2017. Might feed into future NOx standard work.</td>
</tr>
<tr>
<td></td>
<td>Supersonics airport noise and emissions standards</td>
<td>Adopting subsonic noise/emissions standards in separate chapters. Earliest implementation 2024?</td>
</tr>
<tr>
<td>CAEP12 2022</td>
<td>Potential new engine NOx standards Sonic Boom Noise Standards</td>
<td>Earliest implementation 2026?</td>
</tr>
</tbody>
</table>
Sustainable Aviation Air Quality report

Initiatives to reduce emissions at and near to UK airports:

- Retail deliveries are bulked up at consolidation centres, reducing the number of HGV journeys into airports.
- Improved coordination of aircraft movements reduces delays and emissions from taxing aircraft.
- Airports are supporting ultra-low emission vehicles, including electric vehicle charging points and hydrogen fueling.
- Airports are training staff to drive more efficiently, reducing emissions and improving passenger comfort.
- More aircraft are now taxiing to and from the ramp with engines off, reducing emissions and noise.
- More aircraft are now taxiing to and from the ramp without using their engines, reducing emissions and noise.
- Where available, parked aircraft use electrical power and conditioned air from airport terminals to reduce emissions and noise.
- Airports are investing significantly in public transport to make access for passengers and staff easier and more sustainable.
- Communities near airports also benefit from enhanced public transport, reducing emissions from non-airport journeys.
- Airport staff are reducing emissions from commuting through flexible working, car sharing and zero-emission options such as walking or cycling.
- Renewable energy technologies and more efficient boilers reduce emissions from operating airports.
- Cleaner or zero-emission aircraft handling equipment and airport vehicles are being introduced to replace diesel versions.
- Airlines are now flying a new generation of efficient aircraft, with manufacturers already developing the next.
All combustion particles are less than 0.1 microns (less than 100nm).
Particulate Matter - Definition

Small solid and liquid particles suspended temporarily in the air → soot, smoke, dust or droplets of oil and fuel

<table>
<thead>
<tr>
<th>Particulate Type</th>
<th>Size Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td>&lt;10µm</td>
</tr>
<tr>
<td>Fine Particulate PM&lt;sub&gt;2,5&lt;/sub&gt;</td>
<td>&lt;2.5µm</td>
</tr>
<tr>
<td>Ultra fine Particulate PM&lt;sub&gt;0,1&lt;/sub&gt;</td>
<td>&lt;0.1µm</td>
</tr>
<tr>
<td>Nano-particulate PM&lt;sub&gt;0,03&lt;/sub&gt;</td>
<td>&lt;0.03µm</td>
</tr>
</tbody>
</table>

A/C produce:

→ Non Volatile particulates in the combustion chamber from aromatics in fuel
→ Non Volatile particulates from tyres, brakes
→ Volatile particulates in the plume from sulphur in fuel

Rolls-Royce proprietary information
PM – General Health effects

Air pollution:

→ Overall decrease of PM$_{10}$ / PM$_{2.5}$ emissions
→ But still: 98% urban population above WHO limit for PM$_{10}$

Premature deaths (global):

→ PM$_{10}$ / PM$_{2.5}$ = 1 million in 2000 (3rd cause)
→ Urban Air Pollution = top env. cause by 2030

Evidence for PM$_{2.5}$ - UFP & NP suspected to be worse
→ Air pollution / PM$_{2.5}$: Group 1 human carcinogens (WHO-10/2013)
Drivers for reducing ultrafine PM

• “The main concern is related to ultrafine exhaust particles from aircraft and diesel engines.
• Ultrafine diesel particles are known to cause cancer, heart disease, blood clots, brain haemorrhage and airway diseases (bronchitis, COPD), thereby increasing the risk of serious work related illness and premature death.
• However, not much is known about the toxicity of ultrafine particles from aircrafts
  - “Persons working close to exhaust from aircraft engines (main engines and the APU: Auxiliary Power Unit) and/or diesel engines (vehicles, handling and loading equipment etc.) in airports are exposed to a complex mixture of potential health damaging air pollution.”
  - The first study documenting that these persons have an increased occurrence of DNA-damages was released five years ago. The National Board of Industrial Injuries in Denmark has now recognised several cancer cases could have* caused by air pollution in airports. “

*At least one person who died of lung cancer was a heavy smoker

AIR POLLUTION IN AIRPORTS Ultrafine particles, solutions and successful cooperation – the Danish Eco-Council
Drivers for reducing fuel sulphur - health

- SO₂ itself can cause eye irritation and inflammation of the respiratory tract, aggravating asthma and chronic bronchitis and increasing susceptibility to respiratory tract infections.
- Days with higher SO₂ levels also correspond to increased hospital admissions for cardiac disease and mortality [WHO http://www.who.int/mediacentre/factsheets/fs313/en/]
- SOx emissions also give rise to elevated PM2.5 concentrations via the formation of sulphate aerosol.
- The majority of aviation-attributable PM2.5 exposure is related to secondary aerosols rather than primary PM.
- For certification, exhaust primary nvPM is measured, but not the secondary PM which forms downstream

Net LAQ impact of reducing fuel sulphur: Beneficial

Note: Even in a scenario in which aviation fuel sulphur becomes substantially reduced from today’s levels, aviation-attributable ground-level sulphate aerosol, arising from NOx-induced oxidation of non-aviation SOx, is still relevant
Drivers for reducing Sulphur and aromatics – PM2.5

• European Commission report conclusions:
  • “ICAO forecasts doubling of pax numbers over 20 years. “
  • “This vast increase is expected to have a similarly drastic effect on air quality, and therefore on the environment and human health”
  • “aviation emissions contain fine particulate matter (PM2.5) and precursors of ozone (O₃).”
  • “Exposure to PM2.5 and O₃ from aviation emissions could be responsible for approximately 16 000 premature deaths every year. “
  • “Of these, the vast majority (87%) could be linked to PM2.5”
Particulate Matter – Climate impacts

**Direct effects:**
- Black carbon = absorption - warming effect
- Sulphate = reflection - cooling effect

**Indirect effects:**
- Formation of contrails and soot cirrus
- Modification of natural cirrus properties

**Impact on climate is complex and still subject to scientific research**
Impact of reducing fuel sulphur - climate

- Sulphur – oxidised to SO$_2$ – sulphur dioxide
- SO$_2$ – further oxidised to SO$_3$ (mostly outside engine)
- SO$_3$ reacts with water, producing H$_2$SO$_4$
- H$_2$SO$_4$ produces sulphate aerosols, reflective properties give negative forcing (Impact of reducing sulphur: warming).
- Sulphuric acid also plays a role in the formation behind aircraft of contrails which influence the radiative imbalance attributable to aviation.

Net climate impact of reducing fuel sulphur: Uncertain / warming

Note: Aviation oxidation (due to NOx emissions) of non-aviation SO$_2$ would remain even in the total absence of sulphur from jet fuel. Science WIP
Mix of hydrocarbons in some novel fuels can be quite different, but still appear to approach “spec”.

(disclosure statement)
Correlation between hydrogen and aromatics content ([15]; NASA & GE 1983)
Hydrogen & aromatic content vs emissions

Emission index for number of particles versus the hydrogen content (left) and the aromatic content (right)

Rolls-Royce Allison T63 Helicopter engine; ASTM material 2013

Lower aromatics – Seal performance

Effect of thermal cycling on sealing force

Effect of thermal cycling and fuel type/aromatics content on sealing force

(data from FAA CLEEN programme)
Impact of fuel treatments to reduce sulphur on fuel composition

<table>
<thead>
<tr>
<th>Properties “made worse”</th>
<th>Properties “improved”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Acidity</td>
</tr>
<tr>
<td>Aromatics &amp; naphthalenes (for effect on aged fuel system elastomers)</td>
<td>Aromatics &amp; naphthalenes (for combustion properties)</td>
</tr>
<tr>
<td>Specific energy (on a volume basis)</td>
<td>Mercaptan sulphur</td>
</tr>
<tr>
<td>Lubricity</td>
<td>Freezing point</td>
</tr>
<tr>
<td>Conductivity (if additives are not used)</td>
<td>Hydrogen content (though not a specification property)</td>
</tr>
<tr>
<td></td>
<td>Smoke point</td>
</tr>
<tr>
<td></td>
<td>Copper corrosion</td>
</tr>
<tr>
<td></td>
<td>Thermal stability</td>
</tr>
<tr>
<td></td>
<td>Water separation</td>
</tr>
</tbody>
</table>

Table 5-3 Impact of the HDS process on specific properties

Specific energy (mass)
Impact of fuel treatments to reduce sulphur on fuel composition – change in aromatics

BP/RR/MOD study (IASH 2011) – hydrotreatment impact

<table>
<thead>
<tr>
<th>Sulphur ppm</th>
<th>Aromatics %v/v</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>22.70%</td>
</tr>
<tr>
<td>10</td>
<td>19.70%</td>
</tr>
</tbody>
</table>

• A significant reduction in fuel aromatic content might be expected following hydrotreatment.

• However, the study demonstrated that reactor conditions resulted in only a minor (13.2%) change in %total aromatics.
Impact of reducing sulphur content on lubricity

The process which removes sulphur also removes the types of molecules which give jet fuels their lubricating ability. Continuous use of lubricity improving additives will almost certainly be needed for civil aircraft or aircraft fuel system modification may be necessary to enable long term running on poor lubricity fuels. The UK specification for Jet A-1, Defence Standard 91-91, has a lubricity requirement based on the level of hydrodesulphurisation and the BOCLE test. To achieve ULS levels it is likely that the specification would require most fuels to have the BOCLE test and that lubricity improving additives would be required to meet the specification. Eight additives are currently approved but their use would incur unquantified but small additional procurement and handling costs for users.
Impact of reducing sulphur content on lubricity

- Note BOCLE WSD max. limit is 0.85mm

(IASH 2011) – hydrotreatment impact

<table>
<thead>
<tr>
<th>Sulphur ppm</th>
<th>BOCLE WSD (mm)</th>
<th>Indicates that use of lubricity additive may become increasingly important moving to ultra low sulphur fuels.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.79</td>
<td></td>
</tr>
</tbody>
</table>
Impact of reducing sulphur content on lubricity

New Zealand Study (CRC Report AV-14-11)
- During and after the lubricity problems in New Zealand Shell collected data for the MoD on the lubricity of a range of jet fuels where sulphur content and refining process was known, Figure 11.

Osman\(^5\) reported the following relationship between sulfur content and BOCLE wear scar diameter, Figure 12.

Figure 11: Data collected by Shell comparing fuel sulfur content with BOCLE wear scar diameter

Figure 12: Jet fuel sulfur content plotted against fuel lubricity measured by BOCLE
Sulphur vs lubricity

- Trace species in jet fuel, such as naphthalene, sulfur and oxygen compounds, can have a major influence on fuel lubricity.
- Sulfur content is not directly indicative of lubricity for a given fuel.
- Poor lubricity is generally linked to the removal of polar compounds during hydrotreatment, especially severe hydrotreatment.
- A very low sulfur fuel is, however, likely to exhibit poor lubricity because of the coincidental removal of polar species during the sulfur removal process.
- Fuels from non-conventional sources, essentially synthesised hydrocarbons, are generally without polar materials and are therefore likely to exhibit poor lubricity.

CRC Report AV-14-11
Alternative Fuels

†Actively engaged approving sustainable novel drop-in fuels to enable wider use
Evaluating potential benefits for local air quality and emissions reduction

Advanced fuels offering emissions benefits for 2050

† To date, 5 alternative fuel processing routes have been cleared through ASTM -more in progress)