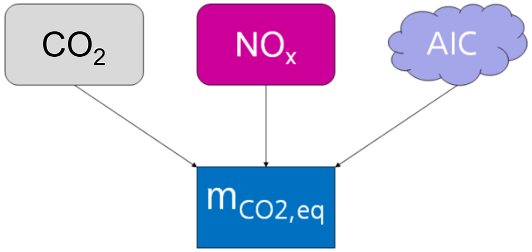
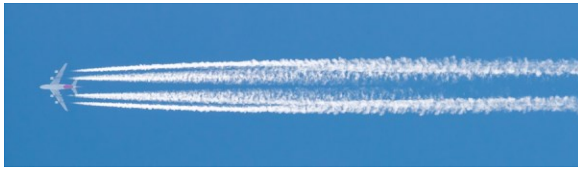
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

The Aircraft and Alternative Modes of Transport – Environmental Impact: Energy Consumption and Global Warming


CO_2
NO_x
AIC
$m_{CO2,eq}$



Dieter Scholz Hamburg University of Applied Sciences

Physikalisches Kolloquium
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Fakultät für Mathematik und Naturwissenschaften
Fachgruppe Physik, 2024-06-10

https://doi.org/10.5281/zenodo.11630497

The Aircraft and Alternative Modes of Transport –
Environmental Impact: Energy Consumption and Global Warming

Abstract

The **environmental impact** of a means of transport is made up of energy consumption, global warming, changes in local air quality, noise and landscape consumption. Global warming in the transport sector is mainly due to the climate impact of CO2. The entire environmental impact of aircraft results from CO2, nitrogen oxides (NOx) and cloud formation due to contrails. This is summarized with the help of the equivalent CO2. Statistically speaking, the environmental impact can be greatly reduced, especially by flying lower.

Contrails occur depending on altitude, air temperature, and humidity. Contrails are only persistent, if the relative humidity exceeds a certain value. It is the typical passenger aircraft with jet engines that cause contrails in cruise flight. Only a few of these contrails would have to be avoided in order to significantly reduce the environmental impact. Global warming caused by passenger jets is three times as high as CO2 alone. This is a significant environmental disadvantage of the aircraft compared to ground-based traffic.

The **selection of a means of transport** can already be made according to basic physical principles. The wheel-rail system has a clear advantage here. However, aircraft are unrivalled, especially for quickly overcoming the oceans. Ways in which air travelers can reduce their environmental impact are presented. The "Ecolabel for Aircraft" evaluates aircraft in comparison. The "Karman-Gabrielli Diagram" considers also speed in a comparison of modes of transport.

Kurzreferat

Das Flugzeug und seine Alternativen – Umweltwirkung: Energieverbrauch und Erderwärmung

Die **Umweltwirkung** eines Verkehrsmittels setzt sich zusammen aus Ressourcenverbrauch (für den Bau des Fahrzeugs, insbesondere aber durch den Energieverbrauch im Betrieb), Erderwärmung, Änderung der lokalen Luftqualität, Lärm und Landschaftsverbrauch. Die Erderwärmung ergibt sich im Verkehrswesen insbesondere durch die Klimawirkung des CO2. 1 kg Kerosin (oder Diesel) verbrennt zu 3,15 kg CO2. Der Energieverbrauch oder speziell der Kraftstoffverbrauch hat also eine doppelte Umweltwirkung einerseits durch den Verbrauch der endlichen fossilen Energie und andererseits durch die Erzeugung von Treibhausgasen. Der Kraftstoffverbrauch von Flugzeugen ergibt sich aus dem Luftwiderstand (Aerodynamik), dem spezifischen Kraftstoffverbrauch (Triebwerkskunde) und der Flugzeugmasse (Leichtbau). Konkrete Werte zum Kraftstoffverbrauch von Flugzeugen werden öffentlich nicht angegeben. Der Kraftstoffverbrauch lässt sich aber bereits abschätzen aus wenigen Flugzeugparametern, die öffentlich bekannt sind. Die gesamte Umweltwirkung ergibt sich aus CO2, den Stickoxiden (NOx) aus der heißen Verbrennung und durch Wolkenbildung aufgrund von Kondensstreifen (Aviation-Induced Cloudiness, AIC). Dies wird mit Hilfe der äquivalenten CO2 zusammengefasst, die abhängig sind von der Flugstrecke und von der Flughöhe. Statistisch gesehen kann die Umweltwirkung insbesondere durch niedrigeres Fliegen stark verringert werden.

Kondensstreifen treten nach dem Schmidt-Appleman Criterion (SAC) auf, abhängig von der Flughöhe, der Lufttemperatur und der Luftfeuchtigkeit. Langlebig sind die Kondensstreifen nur dann, wenn die relative Luftfeuchtigkeit zusätzlich zum SAC einen bestimmten (temperaturabhängigen) Wert überschreitet ausgedrückt durch das Persistent Contrail Criterion (PCC). Langlebig und sich ausbreitend und damit klimawirksam sind Kondensstreifen, wenn durch Turbulenz mehr Feuchtigkeit kondensiert als es dem Wasser aus dem Verbrennungsprozess entspricht. Propellerflugzeug fliegen so tief, dass es kaum zur Bildung von Kondensstreifen kommt. Business Jets fliegen im Reiseflug so hoch und in so trockener Luft, dass es in der Regel nur zu kurzlebigen Kondensstreifen kommt. Es sind die typischen Passagierflugzeuge mit Strahltriebwerken, die Kondensstreifen im Reiseflug verursachen. Kondensstreifen können kühlend wirken oder wärmend. Wenige Kondensstreifen sind wärmend. Trotzdem überwiegt die Wirkung wärmender Kondensstreifen. Stark wärmende Kondensstreifen findet man insbesondere in der Nacht. Nur wenige dieser Kondensstreifen müssten vermieden werden, um die Wirkung deutlich zu reduzieren. Das geschieht durch Höhenänderung zur Vermeidung der PCC-Gebiete. Vereinfachend wird angenommen, dass durch NOx und insbesondere AIC die Erderwärmung bei Passagierjets dreimal so hoch ist, wie durch CO2 allein. Das ist ein erheblicher Umweltnachteil des Flugzeugs gegenüber dem bodengebundenen Verkehr.

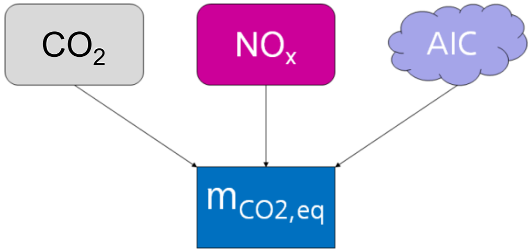
Die **Wahl des Verkehrsmittels** kann bereits nach den physikalischen Grundprinzipien geschehen. Das System Rad-Schiene hat hier einen klaren Vorteil. Insbesondere zum schnellen Überwinden der Ozeane sind Flugzeuge aber konkurrenzlos. Vorgestellt werden Möglichkeiten, mit denen Flugreisende ihre Umweltwirkung verringern können. Eine Flugreise sollte, so weit möglich, als Direktflug gewählt werden. Das "Ecolabel for Aircraft" bewertet Flugzeuge im Vergleich. Das "Karman-Gabrielli-Diagramm" berücksichtigt auch die Geschwindigkeit im Vergleich der Verkehrsträger.

PCC (auch): Potential Contrail Coverage

Contents

Contents (continued)

Environmental Impact

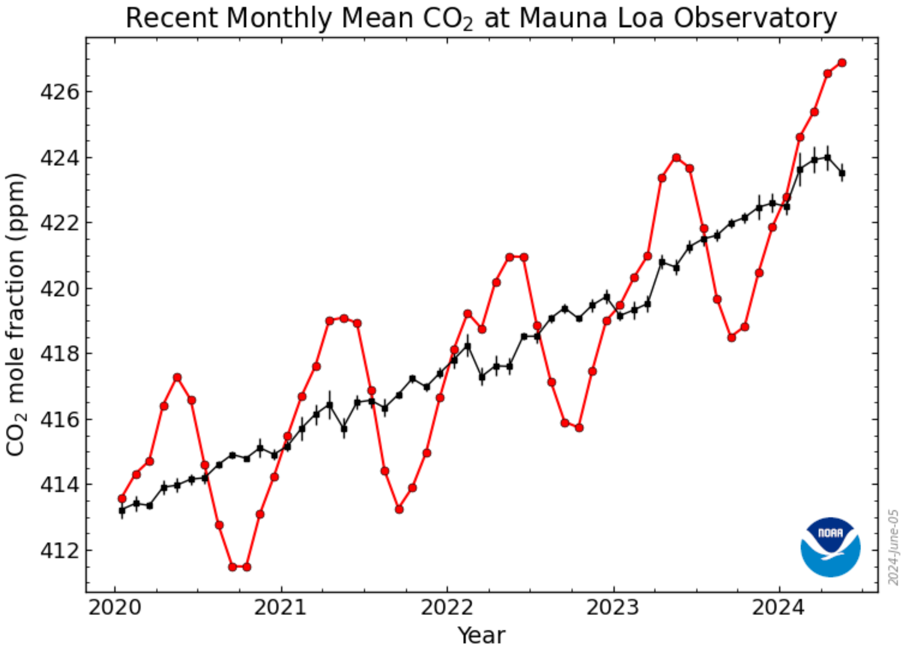


Global Warming:
Time to Act until 2050?

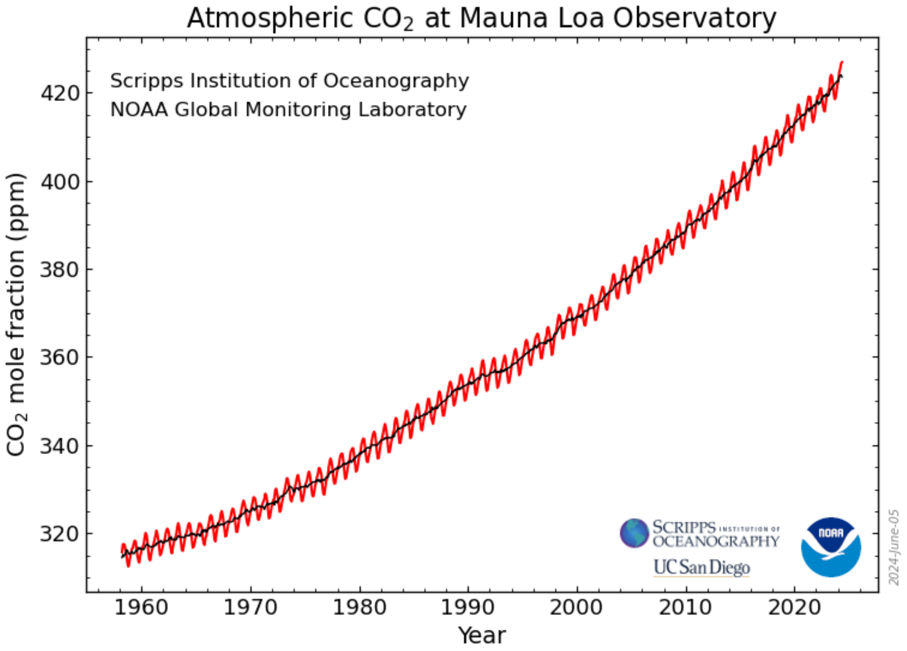
Latest CO2 Data

Mauna Loa, Hawaii

May 2024: 426.90 ppm
May 2023: 424.00 ppm
Last updated: Jun 05, 2024



Recent Monthly Mean CO_2 at Mauna Loa Observatory

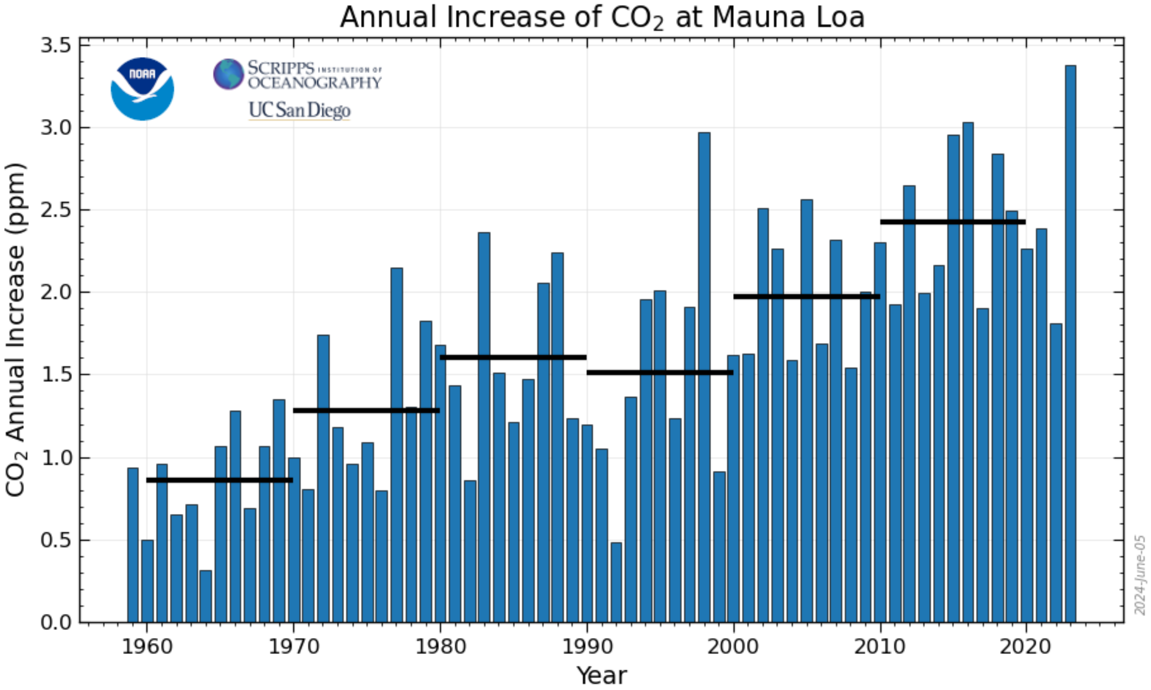


Atmospheric CO_2 at Mauna Loa Observatory

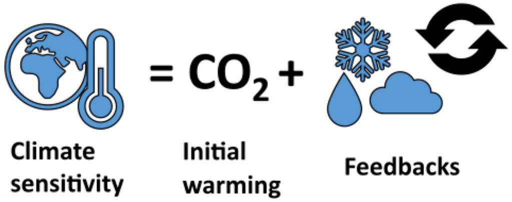
Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory

Base: Pre-industrial (1850-1900), 280 ppm, temperature change: 0 °C

Latest CO2 Data and Climate Sensitivity



2.5 ppm/year



Climate sensitivity is a key measure in climate science and describes how much Earth's surface will warm for a doubling in the atmospheric carbon dioxide (CO2) concentration. In other words, due to an increase from 280 ppm to 560 ppm (plus 280 ppm).

3 °C (+/- 1.5)°C / 280 ppm

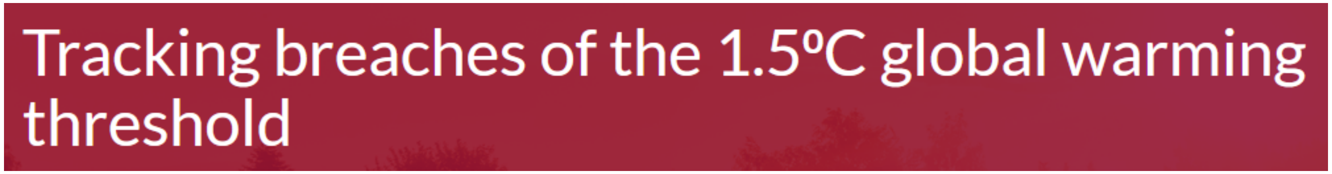
3.0 °C / 280 ppm = 0.0107 °C/ppm

≈ **0.01 °C/ppm**

https://en.wikipedia.org/wiki/Climate_sensitivity

Latest Temperature Data

2023: Climate Change Service



Tracking breaches of the 1.5ºC global warming threshold

https://climate.copernicus.eu/tracking-breaches-150c-global-warming-threshold

2.5 ppm/year

May 2024: 426.90 ppm

May 2023: 424.00 ppm

Last updated: Jun 05, 2024

Calculating the climate sensitivity from 424 ppm – 280 ppm = 144 ppm:

1.5 °C / 144 ppm = 0.01042 °C/ppm

Additional 0.5 °C need 144 ppm/3 = 48 ppm. Hence:

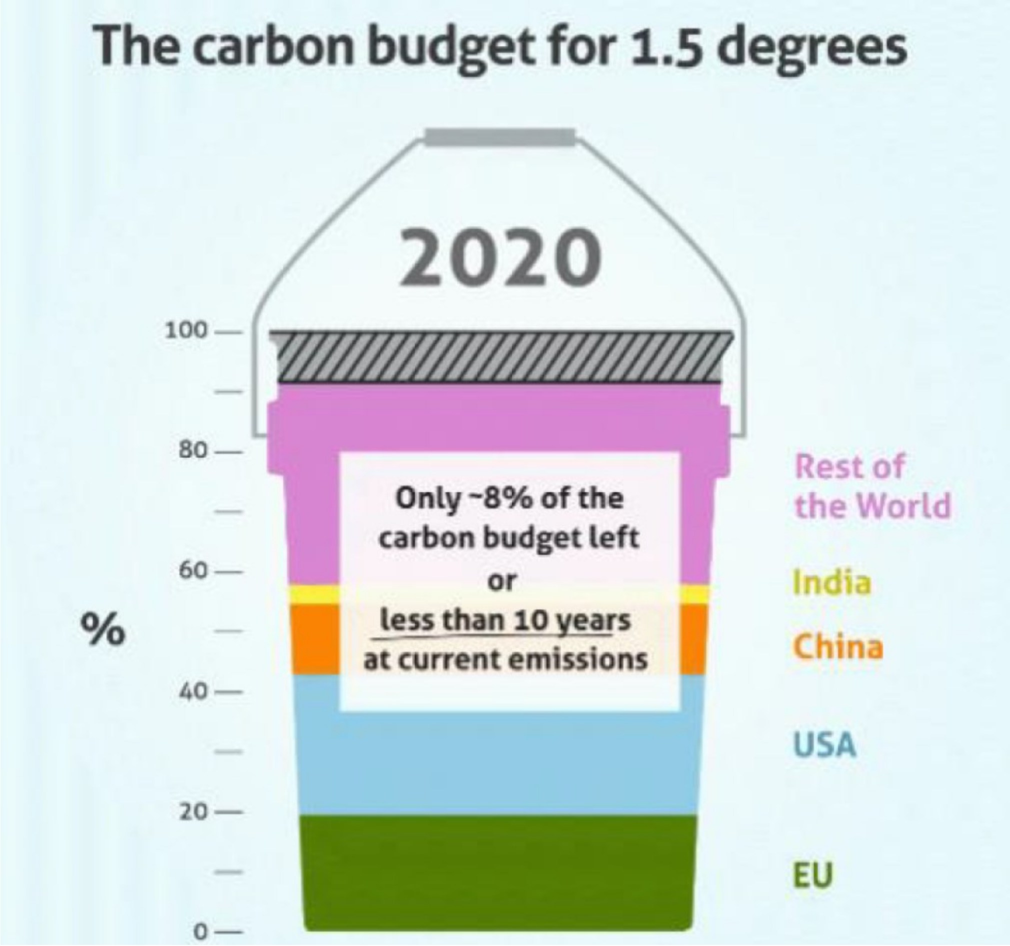
2.0 °C threshold after further 48 ppm or after 48/2.5 years = 19 years

2023 + 19 => 2.0 °C threshold reached in 2042

1 ppm CO2 in the atmosphere is equivalent to 17.3 Gt of CO2 emissions

COOK, John [Skeptical Science], 2024. Comparing CO2 emissions to CO2 levels. Archived at: https://perma.cc/ZFM7-ZUE5

Forecast in 2020 – Way Off



"less than 10 years" left

was finally

"3 years" left,

because

1.5 °C threshold

was already reached in 2023

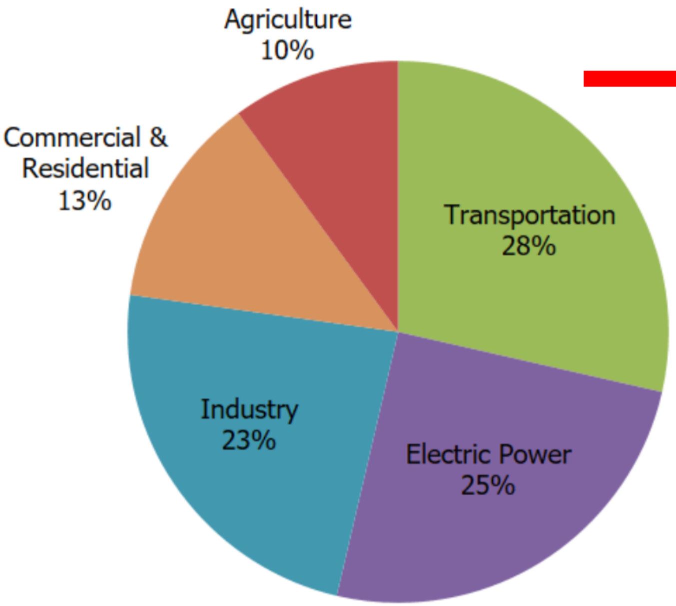
Stanford University and others:
https://youtu.be/aD0EgwohZwg

Decoding Aviation's Climate Challenge

"Contribution of global aviation in 2011 was calculated to be 3.5% of the net anthropogenic Effective Radiative Forcing (ERF)."

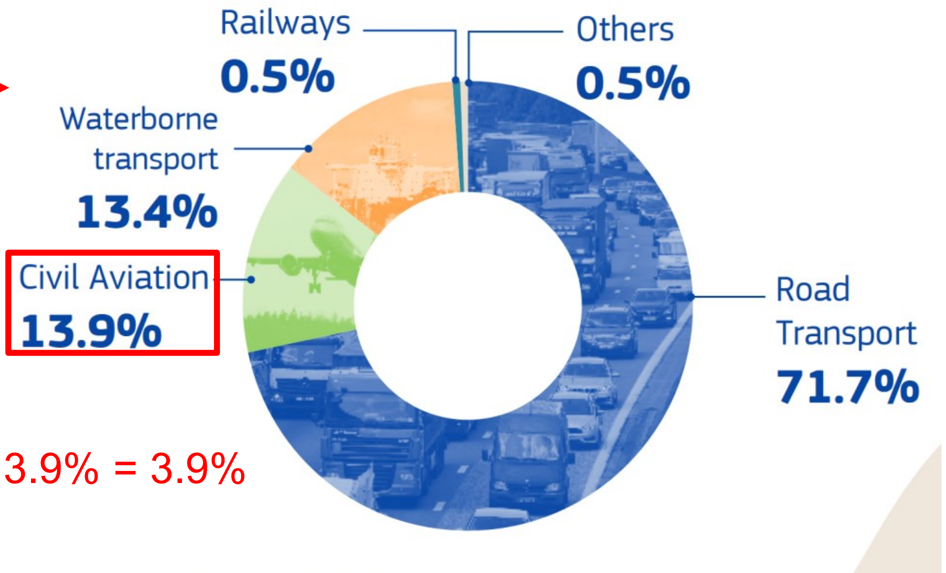
Lee 2020, https://doi.org/10.1016/j.atmosenv.2020.117834

What is 100% ?



https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

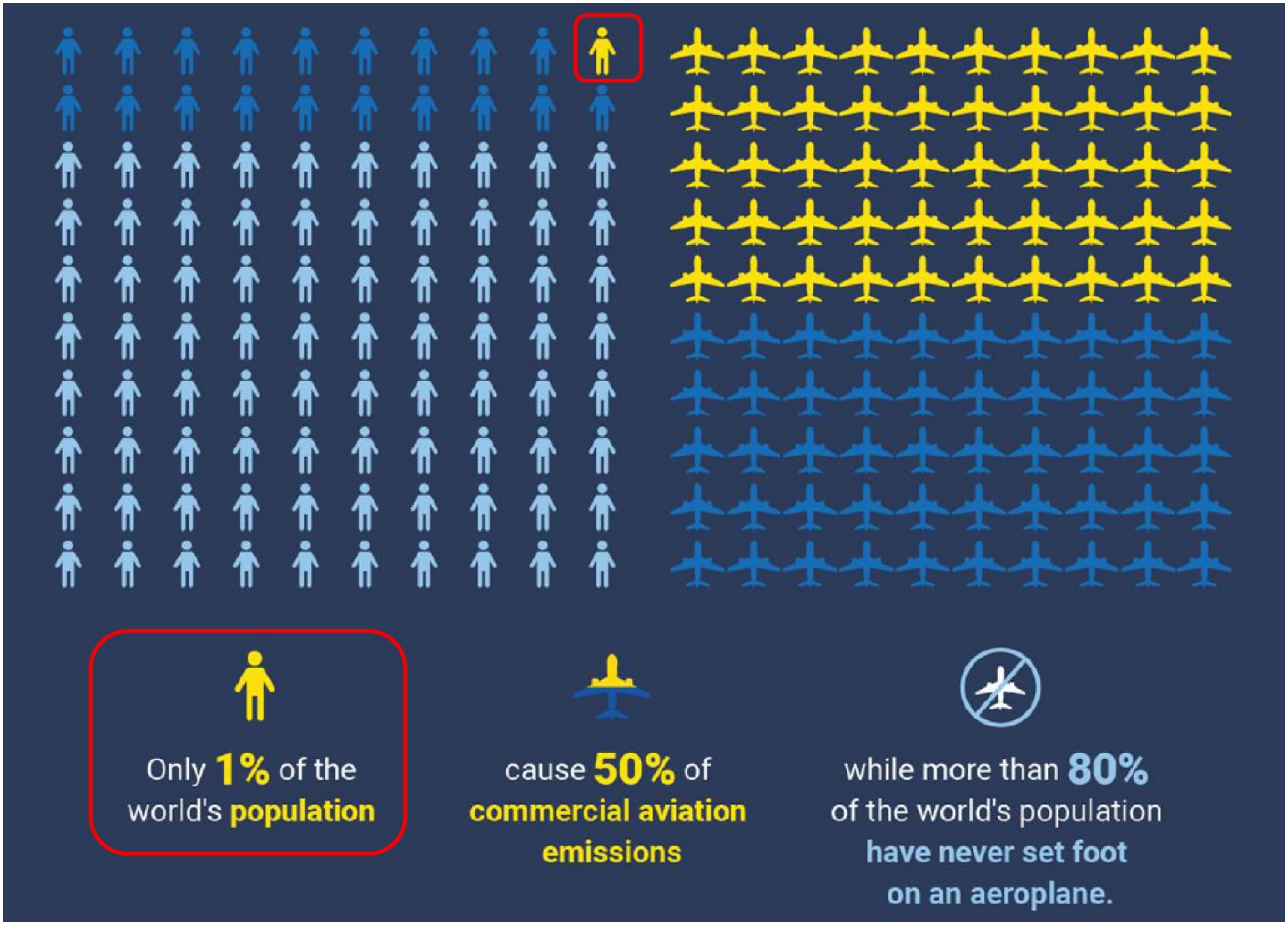
Share of Greenhouse Gas Emissions by Mode of Transport (2017)



Source: Statistical pocketbook 2019

https://doi.org10.2775/395792

28% of 13.9% = 3.9%



Only **1%** of the world's **population**

cause **50%** of **commercial aviation emissions**

while more than **80%** of the world's population **have never set foot on an aeroplane.**

https://stay-grounded.org/get-information

What Matters?

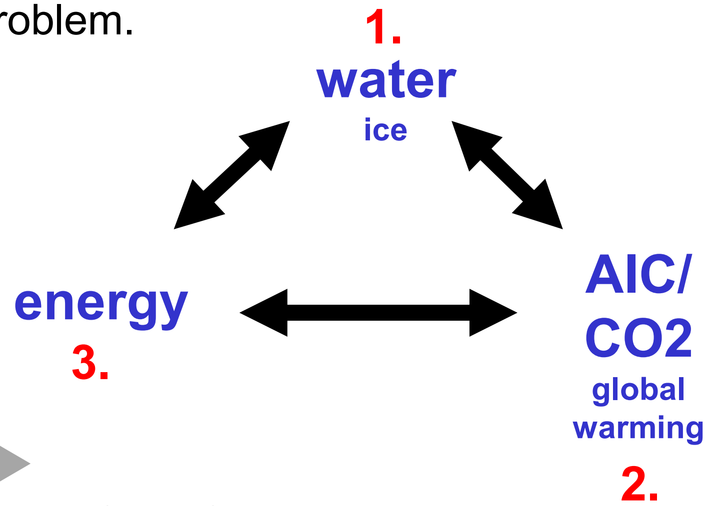
What Matters?

Current focus: Global warming (**CO2**) and **energy**, but:

1. **For human survival it is** not about energy or CO2, but **about clean drinking water**!
2. **In aviation related to** global warming not primarily about CO2 but it is **about Aviation Induced Cloudiness** (**AIC**).
   Aviation has indirectly a water problem not a CO2 problem.

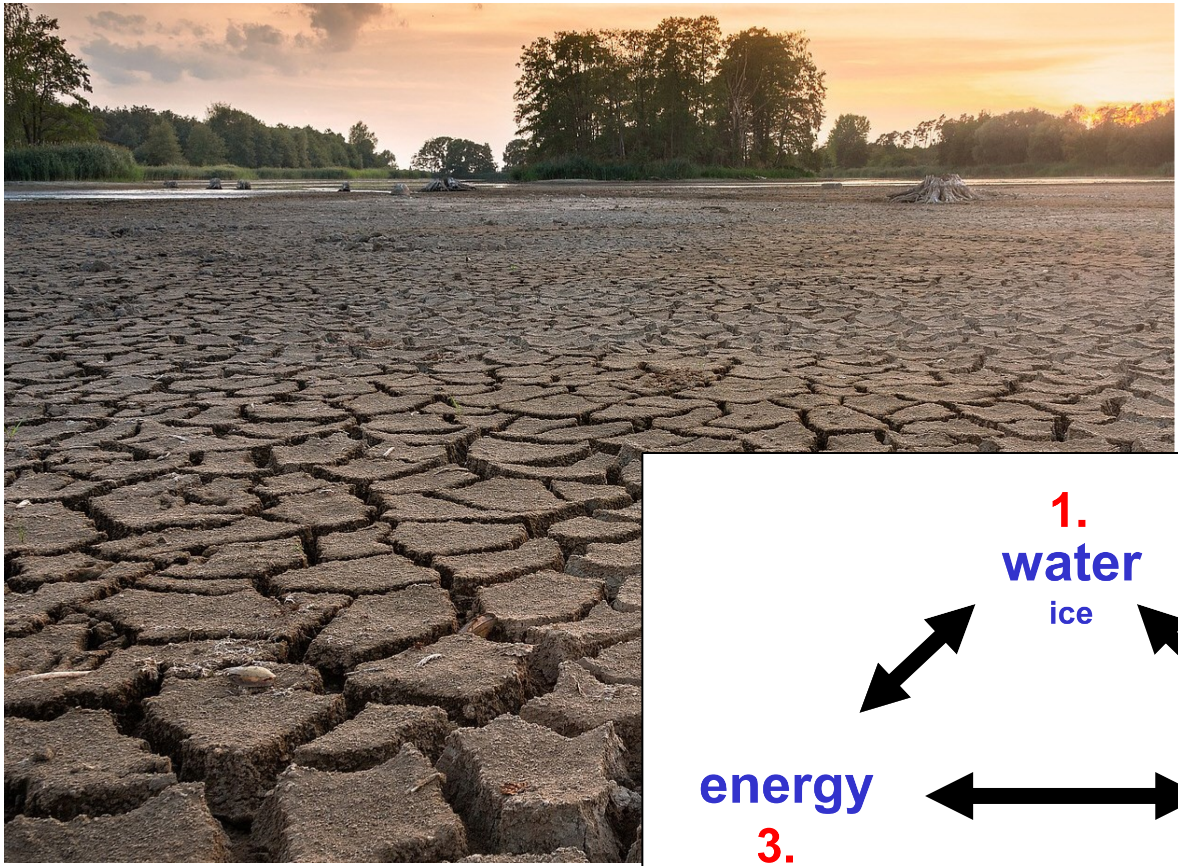
Needed: Balanced look with **Life Cycle Assessment**

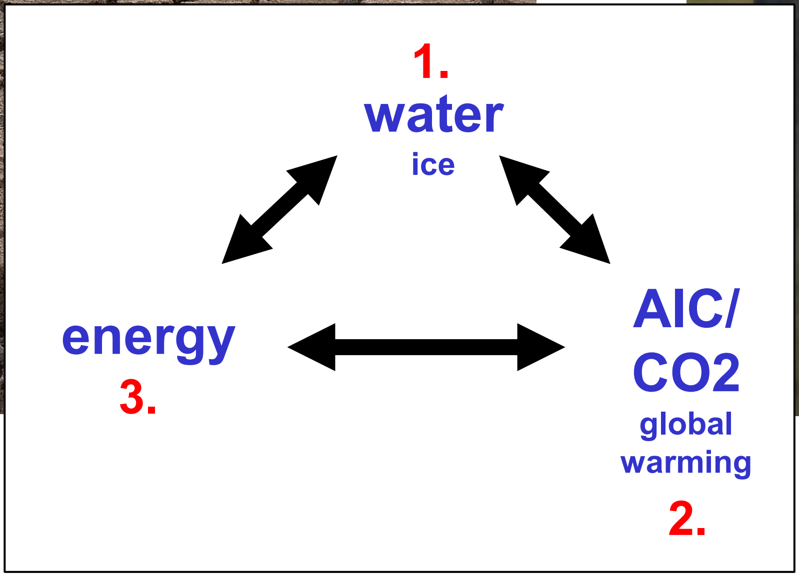
Everything is connected:
melting ice => global warming
global warming => melting ice
fossile energy use => global warming
global warming => less energy for heating
energy use for desalination => water
water usage => energy generation (H2, ...)



In modification of:
SCHOLZ, Dieter, 2012. *Eco-Efficiency in Aviation – Flying Off Course?* German Aerospace Congress 2012 (DLRK2012), Berlin, Germany, 10.-12.09.2012.
Available from: https://doi.org/10.5281/zenodo.4067014

Most Important in General: Clean Drinking Water





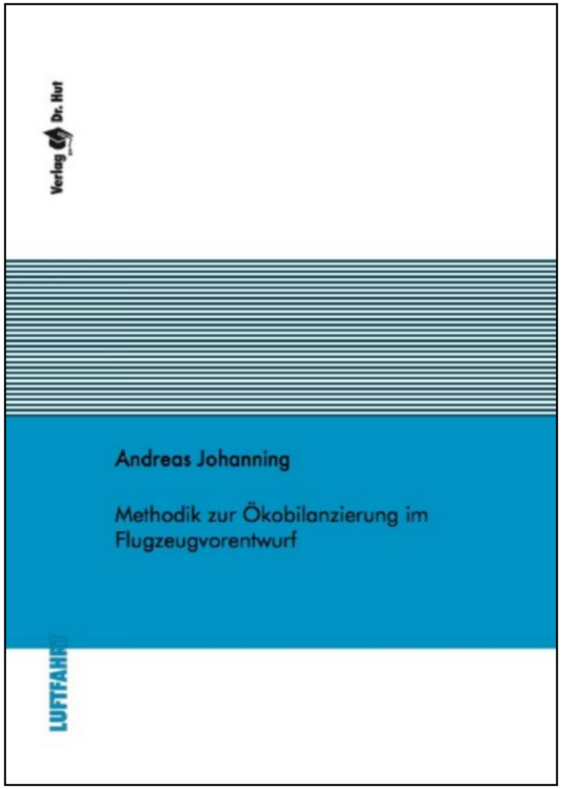
1.
water
ice

energy
3.

AIC/
CO2
global
warming
2.

Life Cycle Assessment in Aviation

Life Cycle Assessment (LCA) Applied to Aviation



Verlag Dr. Hut

Andreas Johanning

Methodik zur Ökobilanzierung im Flugzeugvorentwurf

LUFTFAHRT

Johanning (2017):
Life Cycle Assessment
in Aircraft Design

ISO 14040:2006
Environmental Management -- Life Cycle Assessment

National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

NL

http://www.lcia-recipe.net

ReCiPe

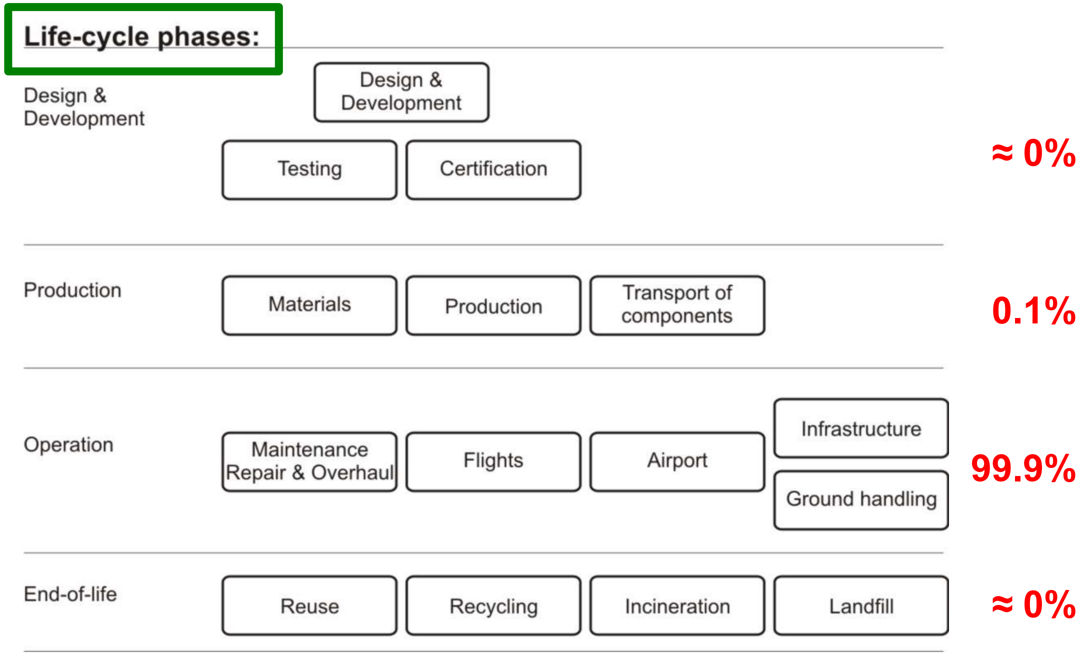
ReCiPe is a method for the impact assessment in a **Life Cycle Assessment** LCA. LCA translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterization factors. There are two ways to derive **characterization factors**, i.e. at midpoint level and at endpoint level. ReCiPe calculates:

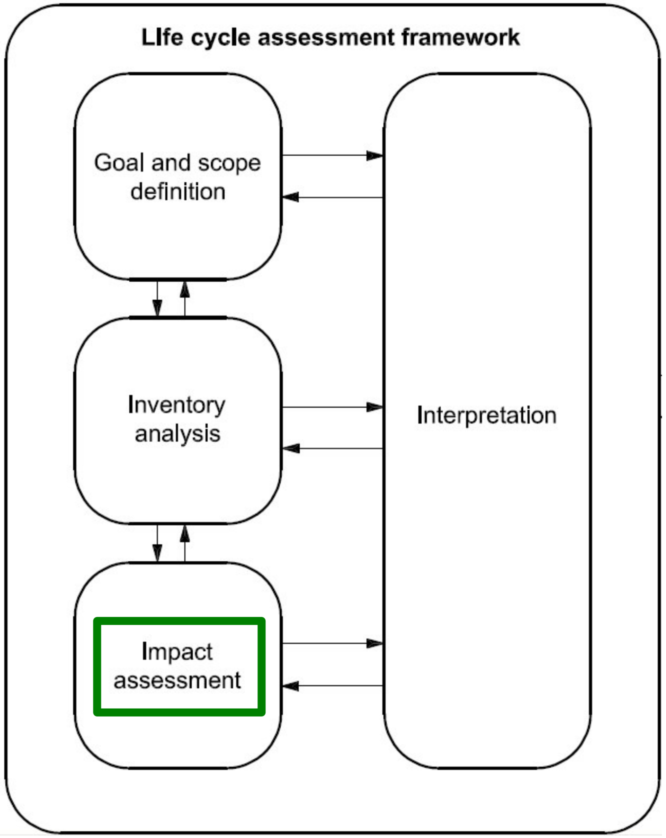
- **18 Midpoint Indicators**
- **3 Endpoint Indicators**
- **1 Single Score**

http://www.fzt.haw-hamburg.de/pers/Scholz/Airport2030/JOHANNING_DISS_Methodik_zur_Oekobilanzierung_im_Flugzeugvorentwurf_2017.pdf

Life Cycle Assessment (LCA) Applied to Aviation

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system during its life cycle"

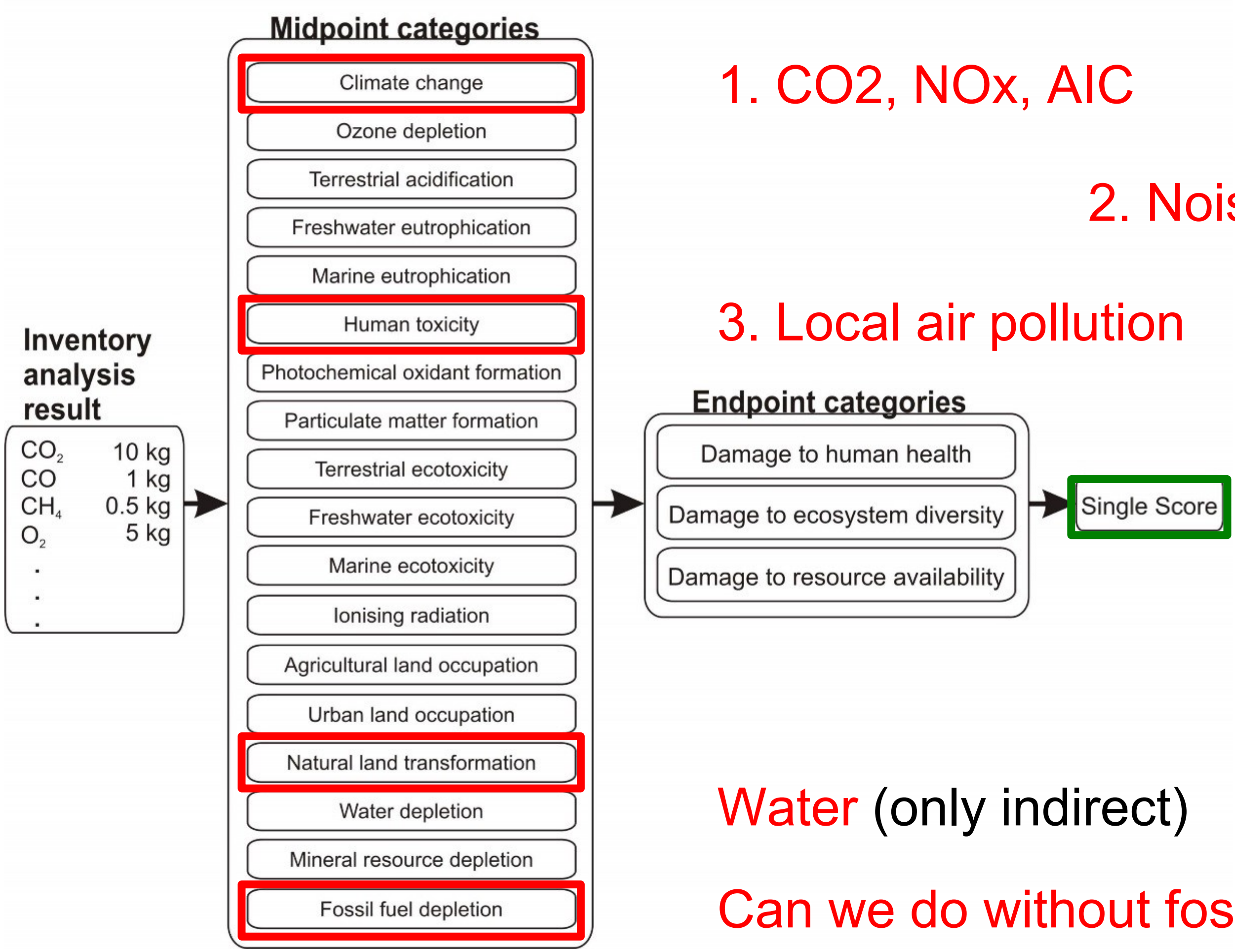




Standardized according to ISO 14040, ISO 14044

INTERNATIONAL STANDARD ORGANISATION, 2006. ISO 14040: *Environmental management — Life cycle assessment — Principles and framework*. July 2006. Available from: https://www.iso.org/standard/37456.html

Impact Assessment in LCA Applied to Aviation



Inventory analysis result

CO_2	10 kg
CO	1 kg
CH_4	0.5 kg
O_2	5 kg
.	
.	
.	

Midpoint categories

- Climate change
- Ozone depletion
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Human toxicity
- Photochemical oxidant formation
- Particulate matter formation
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Ionising radiation
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Water depletion
- Mineral resource depletion
- Fossil fuel depletion

Endpoint categories

- Damage to human health
- Damage to ecosystem diversity
- Damage to resource availability

Single Score

1. CO2, NOx, AIC

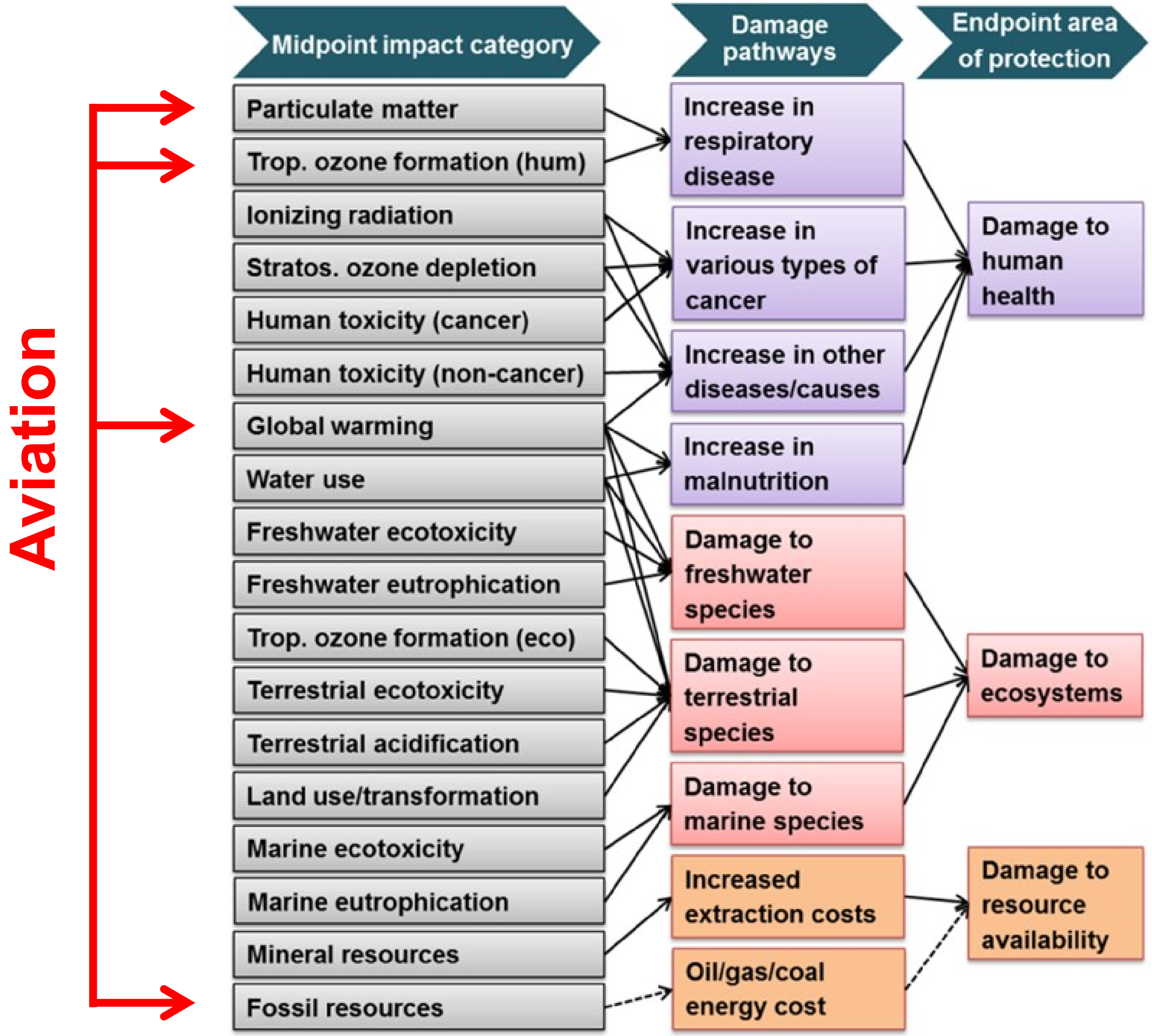
2. Noise! Not included!?

3. Local air pollution

Water (only indirect)

Can we do without fossil fuels?

ReCiPe Method – Available from: https://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf



Aviation

Midpoint impact category

- Particulate matter
- Trop. ozone formation (hum)
- Ionizing radiation
- Stratos. ozone depletion
- Human toxicity (cancer)
- Human toxicity (non-cancer)
- Global warming
- Water use
- Freshwater ecotoxicity
- Freshwater eutrophication
- Trop. ozone formation (eco)
- Terrestrial ecotoxicity
- Terrestrial acidification
- Land use/transformation
- Marine ecotoxicity
- Marine eutrophication
- Mineral resources
- Fossil resources

Damage pathways

- Increase in respiratory disease
- Increase in various types of cancer
- Increase in other diseases/causes
- Increase in malnutrition
- Damage to freshwater species
- Damage to terrestrial species
- Damage to marine species
- Increased extraction costs
- Oil/gas/coal energy cost

Endpoint area of protection

- Damage to human health
- Damage to ecosystems
- Damage to resource availability

ReCiPe

It was added to the basic Method:

1.) by Johanning:
Altitude Dependency

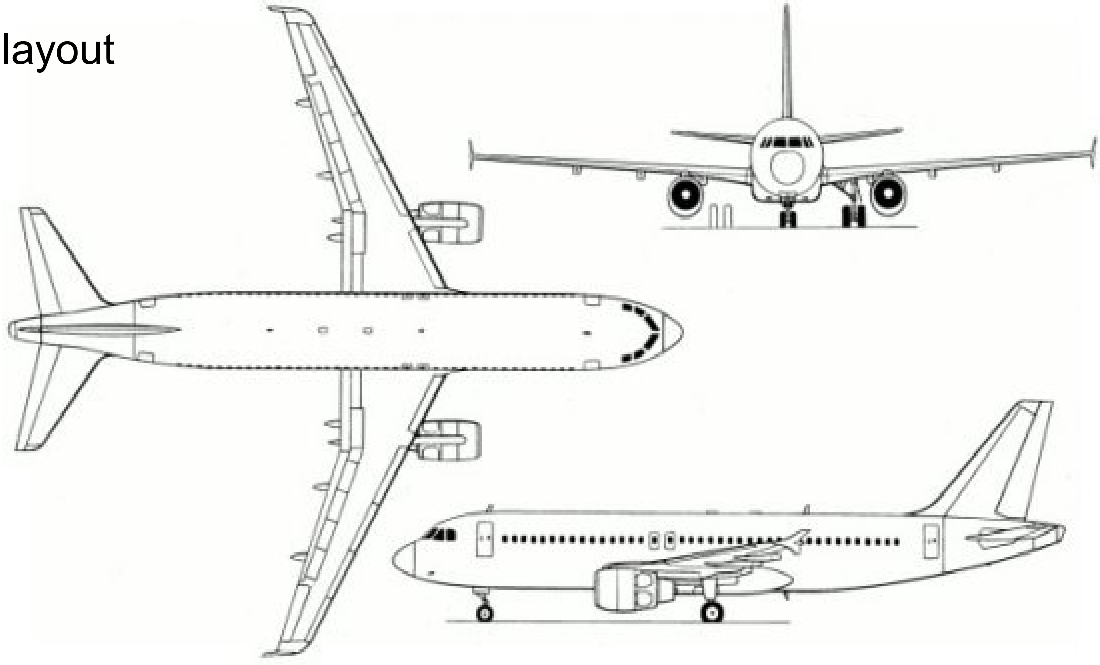
2.) here:
Noise

https://doi.org/10.1007/s11367-016-1246-y

Life Cycle Assessment (LCA) Applied to an Airbus A320

The reference aircraft and its requirements:

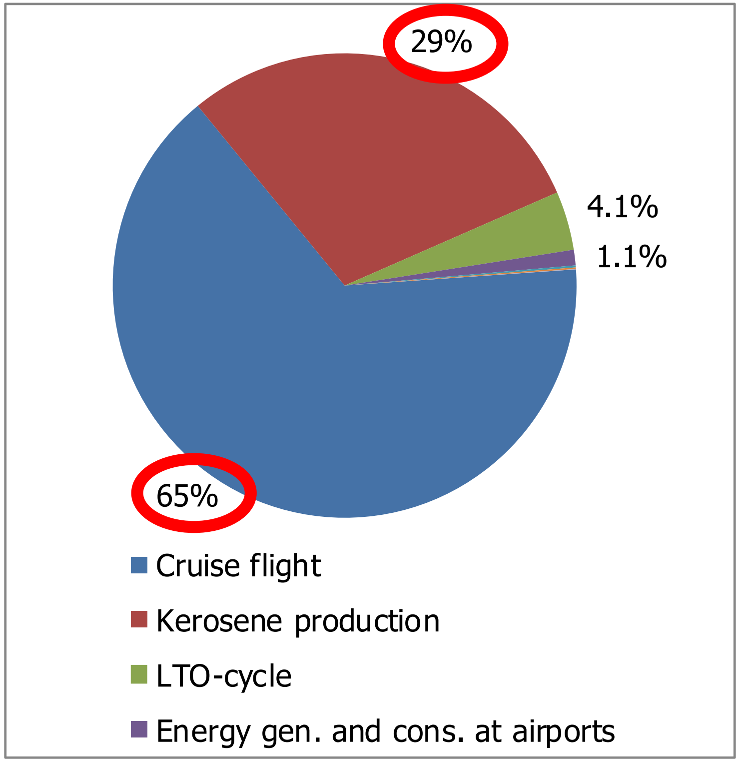
- **Airbus A320-200**, weight variant WV000
- Design range: 1510 NM with a payload of 19256 kg
- 180 passengers in a one-class layout
- Cruise Mach number 0.76



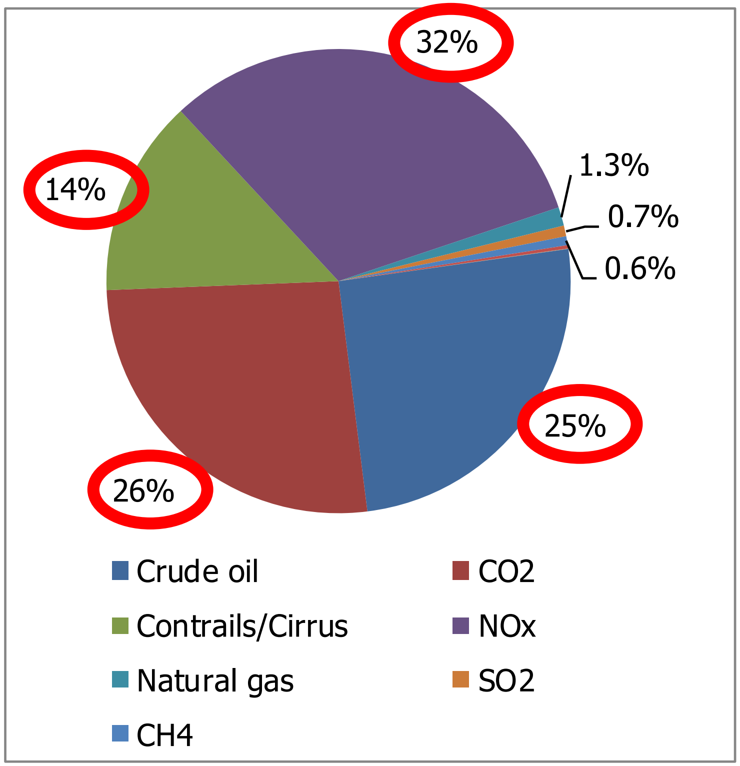
http://www.aerospaceweb.org

Life Cycle Assessment ("Single Score") Results for an Airbus A320

- Cruise flight and kerosene production dominate environmental impact
- CO_2, NO_x, crude oil and contrails/cirrus clouds have highest influence



Life Cycle Processes on Single Score

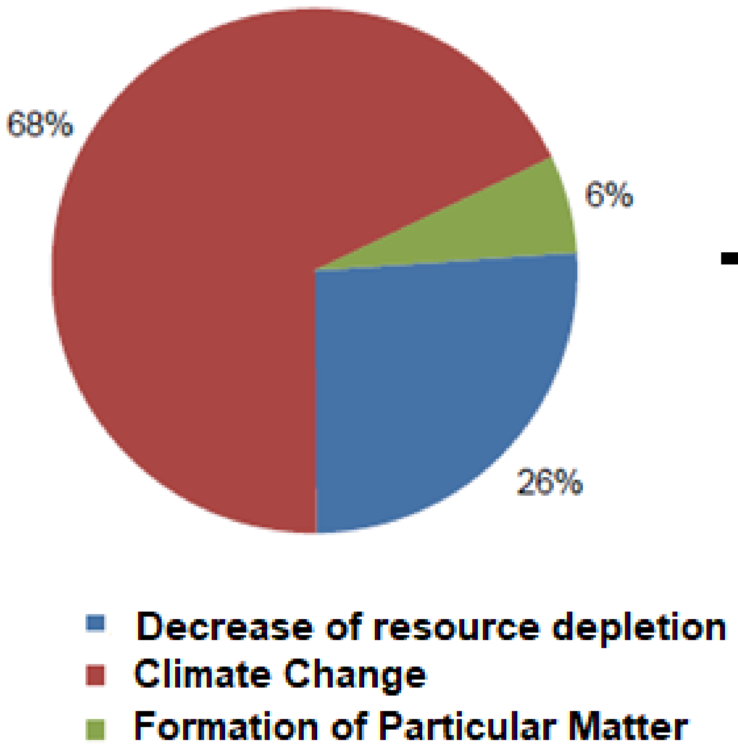


Inventory Analysis (in- and outputs) on Single Score

From Life Cycle Assessment to the Ecolabel for Aircraft

ReCiPe – Result (A320) →

Johanning (2017)



→

Ecolabel for Aircraft

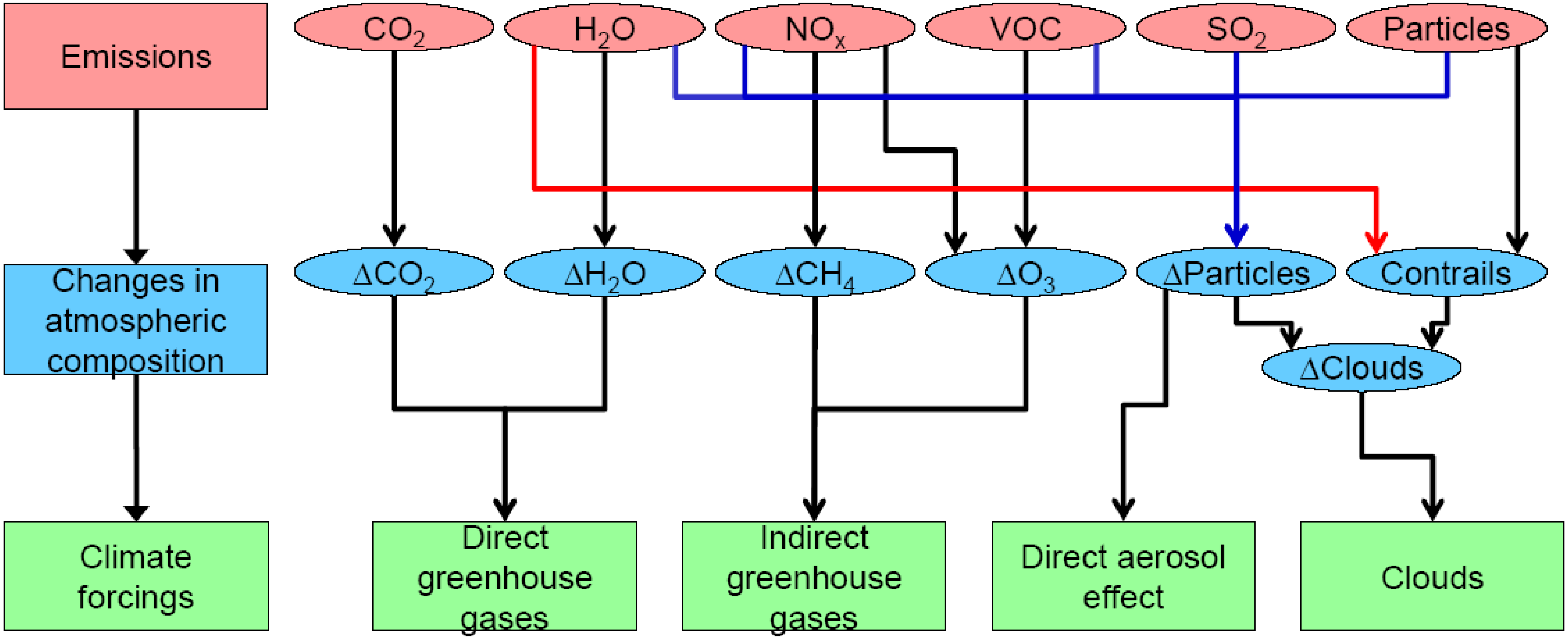
Overall Rating:

$$\boxed{\begin{aligned} R_{overall} = \quad & 0.4 R_{warming} \\ & + 0.2 R_{depletion} \\ & + 0.2 R_{localAir} \\ & + 0.2 R_{noice} \end{aligned}} \quad \longleftarrow$$

1. Global warming (fuel => CO2, NOx, AIC)
2. Resource depletion (aircraft fuel consumption)
3. Local air pollution (fuel => NOx, LTO)
4. Noise (take-off and landing)

Global Warming
due to
Aviation

Aviation Emissions and Climate Impact

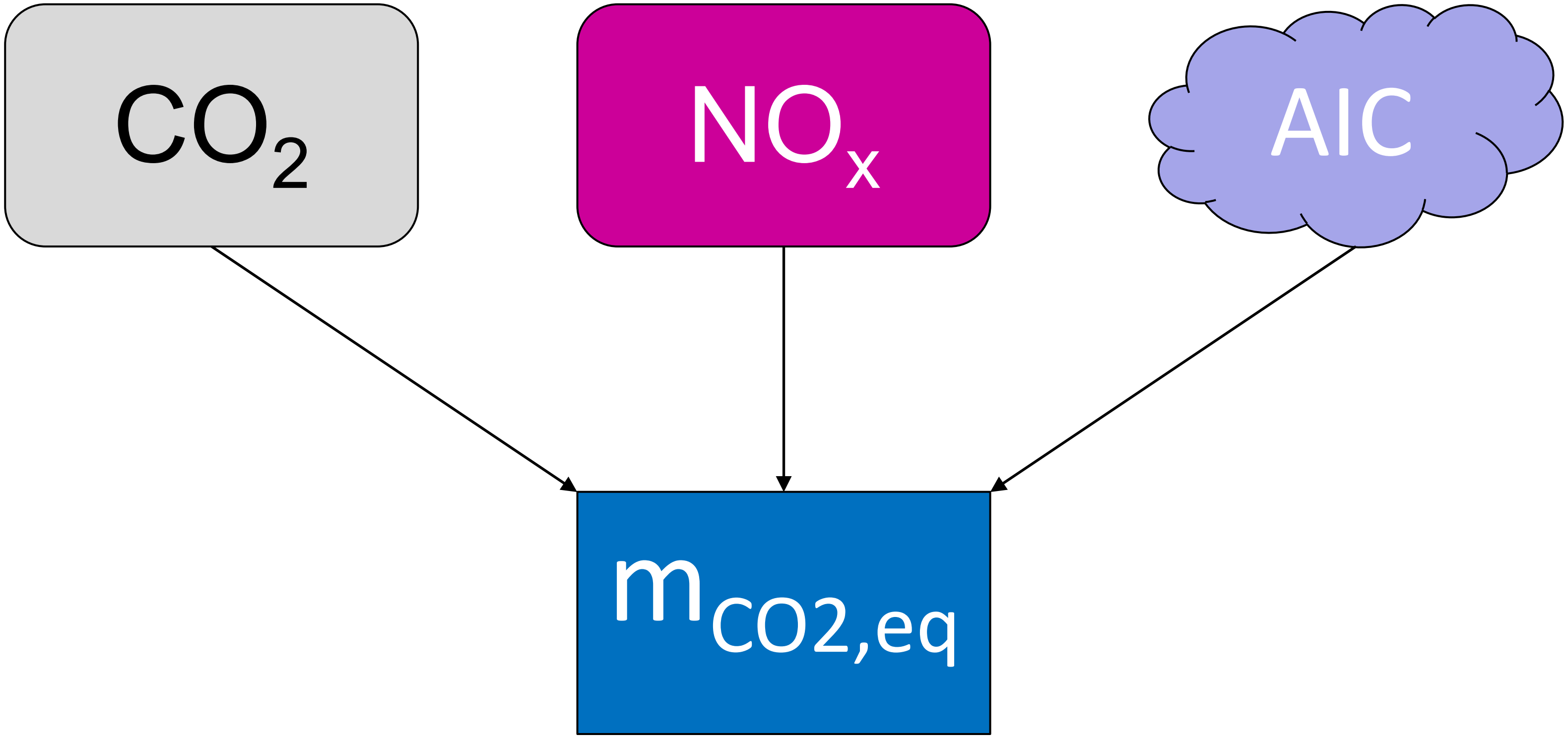


CO2: Long term influence

Non-CO2: Short term influence (immediate mitigation is possible)

RAPP, Markus, 2019. Perspektive: Wasserstoff & Hybride. Meeting: "Emissionsfreies Fliegen-wie weit ist der Weg?", Berlin, 13.11.2019

Global Warming – Measured in Equivalent CO_2 Mass



CO_2

NO_x

AIC

$m_{CO2,eq}$

CAERS, Brecht, SCHOLZ, Dieter, 2020. *Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact*. German Aerospace Congress 2020 (DLRK 2020), Online, 01.-03.09.2020.
Available from: https://doi.org/10.5281/zenodo.4068135

Calculating Altitude-Dependent Equivalent CO2 Mass

$$m_{CO2,eq} = \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat,typical}} \cdot CF_{midpoint,CO_2} + \frac{EI_{NO_x} \cdot f_{NM}}{n_{seat,typical}} \cdot CF_{midpoint,NO_x} + \frac{R_{NM} \cdot f_{NM}}{R_{NM} \cdot f_{NM,ref} \cdot n_{seat,typical}} \cdot CF_{midpoint,AIC}$$

$$f_{NM,ref} = 4.74\ \mathrm{kg/km}$$

MATTAUSCH 2024

Sustained Global Temperature Potential, SGTP (similar to GWP):

$$CF_{midpoint\ ,NOx}(h) = \frac{SGTP_{O_{3S},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,S}(h) + \frac{SGTP_{O_{3L},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,L}(h) + \frac{SGTP_{CH_4,100}}{SGTP_{CO_2,100}} \cdot s_{CH_4}(h)$$

$$CF_{midpoint,AIC}(h) = \frac{SGTP_{contrails\ ,100}}{SGTP_{CO_2,100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus\ ,100}}{SGTP_{CO_2,100}} \cdot s_{cirrus}(h)$$

Species	Emission Index, EI (kg/kg fuel)
CO_2	3,15
H_2O	1,23
SO_2	$2{,}00 \cdot 10^{-4}$
Soot	$4{,}00 \cdot 10^{-5}$

NOx $1.45 \cdot 10^{-2}$ (typical value)

$$s_{O_3,L}(h) = s_{CH_4}(h)$$

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h)$$

SCHWARTZ 2009, JOHANNING 2014

Species	$SGTP_{i,100}$
CO_2 (K/kg CO_2)	$3{,}58 \cdot 10^{-14}$
Short O_3 (K/kg NO_x)	$7{,}97 \cdot 10^{-12}$
Long O_3 (K/NO_x)	$-9{,}14 \cdot 10^{-13}$
CH_4 (K/kg NO_x)	$-3{,}90 \cdot 10^{-12}$
Contrails (K/NM)	$2{,}54 \cdot 10^{-13}$
Contrails (K/km)	$1{,}37 \cdot 10^{-13}$
Cirrus (K/NM)	$7{,}63 \cdot 10^{-13}$
Cirrus (K/km)	$4{,}12 \cdot 10^{-13}$

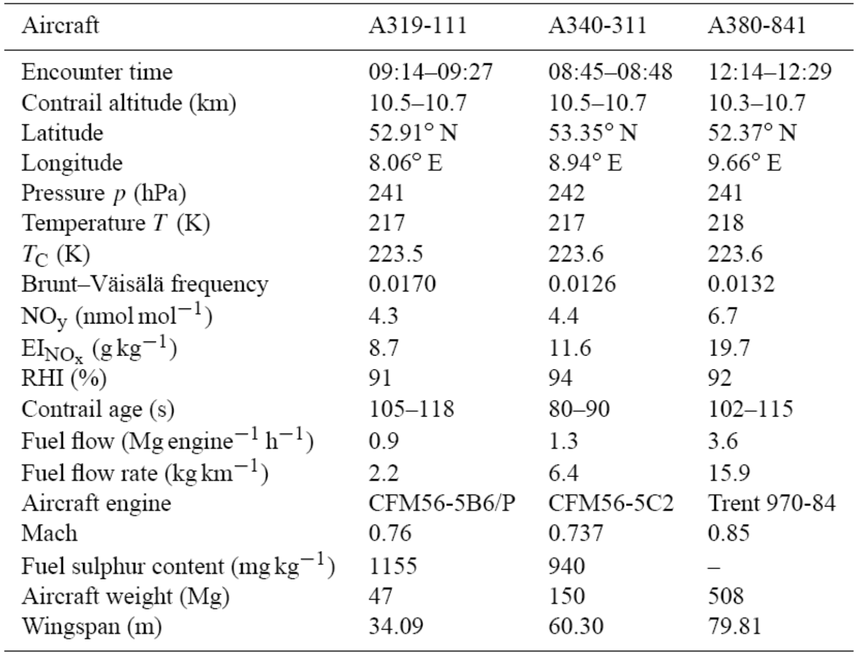
EI	emission index
f_{NM}	fuel consumption per NM or km
R_{NM}	range in NM or km
CF	characterization factor

Cirrus/Contrails = 3.0

water vapor not considered

AIC	aviation-induced cloudiness

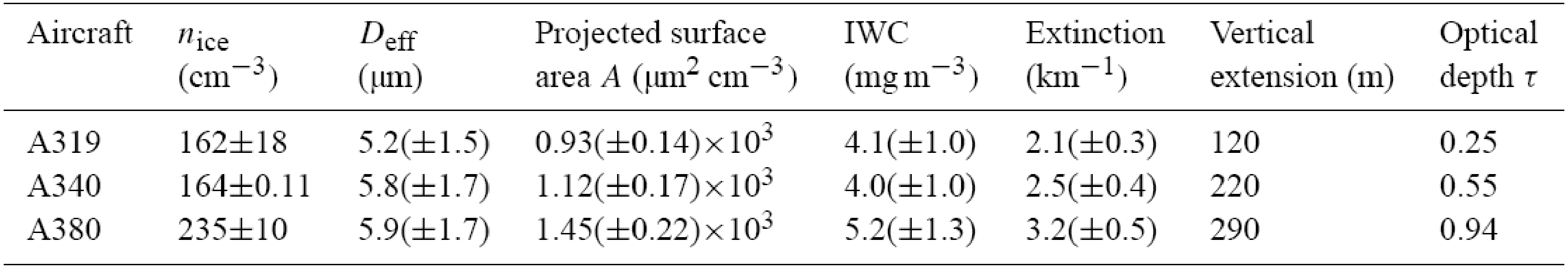
Contrail Radiative Forcing (CRF) as a Function of Fuel Flow (ff)



Aircraft	A319-111	A340-311	A380-841
Encounter time	09:14–09:27	08:45–08:48	12:14–12:29
Contrail altitude (km)	10.5–10.7	10.5–10.7	10.3–10.7
Latitude	52.91° N	53.35° N	52.37° N
Longitude	8.06° E	8.94° E	9.66° E
Pressure p (hPa)	241	242	241
Temperature T (K)	217	217	218
T_C (K)	223.5	223.6	223.6
Brunt–Väisälä frequency	0.0170	0.0126	0.0132
NO_y (nmol mol^{-1})	4.3	4.4	6.7
EI_{NO_x} (g kg^{-1})	8.7	11.6	19.7
RHI (%)	91	94	92
Contrail age (s)	105–118	80–90	102–115
Fuel flow (Mg engine^{-1} h^{-1})	0.9	1.3	3.6
Fuel flow rate (kg km^{-1})	2.2	6.4	15.9
Aircraft engine	CFM56-5B6/P	CFM56-5C2	Trent 970-84
Mach	0.76	0.737	0.85
Fuel sulphur content (mg kg^{-1})	1155	940	–
Aircraft weight (Mg)	47	150	508
Wingspan (m)	34.09	60.30	79.81

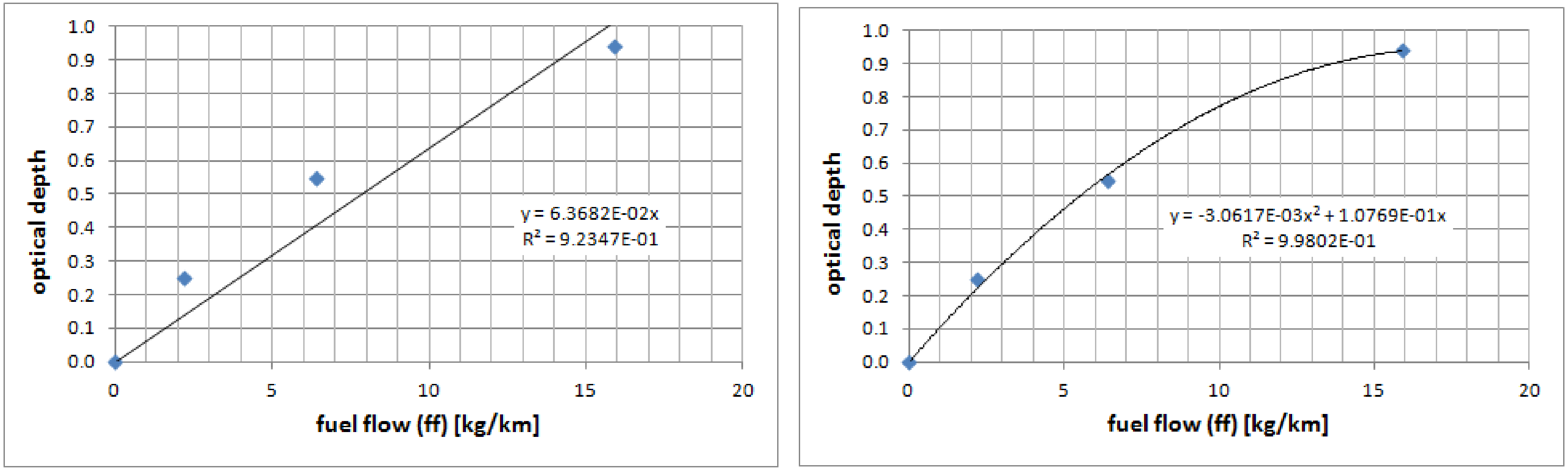
τ		ff	τ / ff [km/kg]	aircraft
0.25	/	2.2	= 0.114	A319
0.55	/	6.4	= 0.0859	A340
0.94	/	15.9	= 0.059	A380

JEßBERGER, Philipp, et al. Aircraft type influence on contrail properties. Atmospheric Chemistry and Physics, 2013, 13. Jg., Nr. 23, S. 11965-11984. Available from: https://10.5194/acp-13-11965-2013



Aircraft	n_{ice} (cm^{-3})	D_{eff} (µm)	Projected surface area A (µm^2 cm^{-3})	IWC (mg m^{-3})	Extinction (km^{-1})	Vertical extension (m)	Optical depth τ
A319	162±18	5.2(±1.5)	0.93(±0.14)×10^3	4.1(±1.0)	2.1(±0.3)	120	0.25
A340	164±0.11	5.8(±1.7)	1.12(±0.17)×10^3	4.0(±1.0)	2.5(±0.4)	220	0.55
A380	235±10	5.9(±1.7)	1.45(±0.22)×10^3	5.2(±1.3)	3.2(±0.5)	290	0.94

Contrail Radiative Forcing (CRF) as a Function of Fuel Flow (ff)



The quadratic regression (right) fits amazingly well. However, from the small number of aircraft tested, no such general law may be derived.

The climate model by SCHWARTZ 2009, which calculates AIC effects only based on contrail length (flight distance) was extended to include fuel burn (in kg/km) into the equation. Fuel burn enters linearly!

SCHWARTZ, Emily, KROO, Ilan M., 2009. *Aircraft Design: Trading Cost and Climate Impact*.
47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition,
05.01.-08.01.2009, Orlando, Florida, AIAA 2009, No.1261. Available from: https://doi.org/10.2514/6.2009-1261

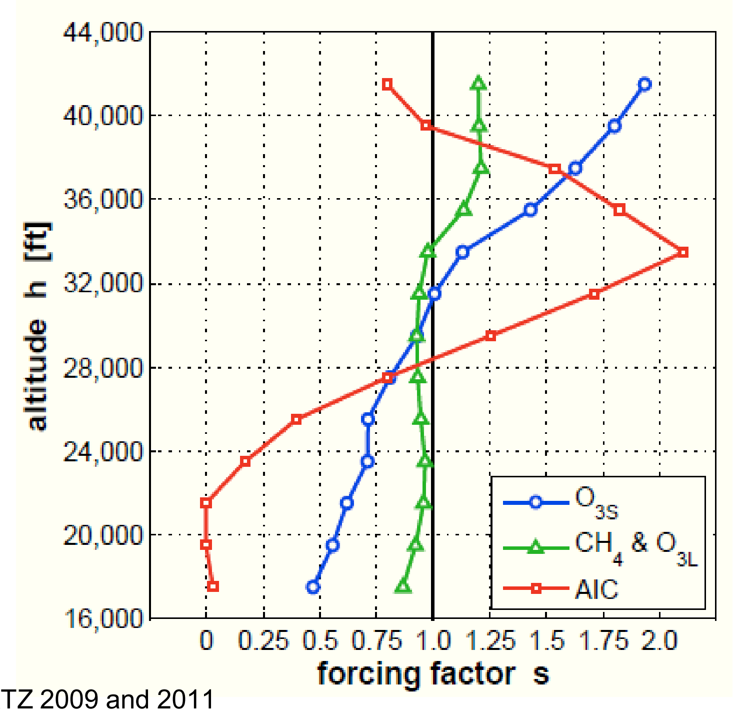
JOHANNING, Andreas, SCHOLZ, Dieter, 2014. *Adapting Life Cycle Impact Assessment Methods for Application in Aircraft Design*.
German Aerospace Congress 2014 (DLRK 2014), Augsburg, 16.-18.09.2014.
Available from: https://nbn-resolving.org/urn:nbn:de:101:1-201507202456. Download: http://Airport2030.ProfScholz.de

Calculating Altitude-Dependent Equivalent CO2 Mass

E.g.: $$CF_{midpoint,AIC}\quad(h) = \frac{SGTP_{contrails\ ,100}}{SGTP_{CO_2,100}} \cdot s_{contrails}\ (h) + \frac{SGTP_{cirrus\ ,100}}{SGTP_{CO_2,100}} \cdot s_{cirrus}\ (h)$$

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h)$$

Forcing Factor *s* = f(*h*)



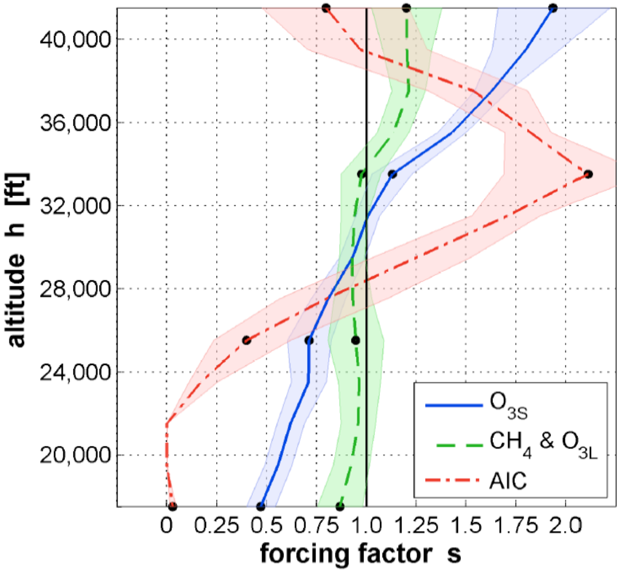
SCHWARTZ 2009 and 2011

- The curves go along with the ICAO Standard Atmosphere (ISA) applicable for average lattitudes. With a first approximation, the curves could be adapted to other lattitudes by stretching and shrinking them proportionally to the altitude of the tropopause.
- The curves from SVENSSON 2004 (Fig. 1) show similar shapes. However, the importance of AIC is not yet as distinct.

SVENSSON, Fredrik, HASSELROT, Anders, MOLDANOVA, Jana, 2004. Reduced Environmental Impact by Lowered Cruise Altitude for Liquid Hydrogen-Fuelled Aircraft. In: *Aerospace Science and Technology*, Vol. 8 (2004), Nr. 4, pp. 307–320. Available from: https://doi.org/10.1016/j.ast.2004.02.004

Calculating Altitude-Dependent Equivalent CO2 Mass

Forcing Factor *s* = f(*h*)



Forcing factors (lines) with **66% likelihood ranges** (shaded areas). Altitudes with forcing factors based on radiative forcing data with independent probability distributions. (SCHWARTZ 2011)

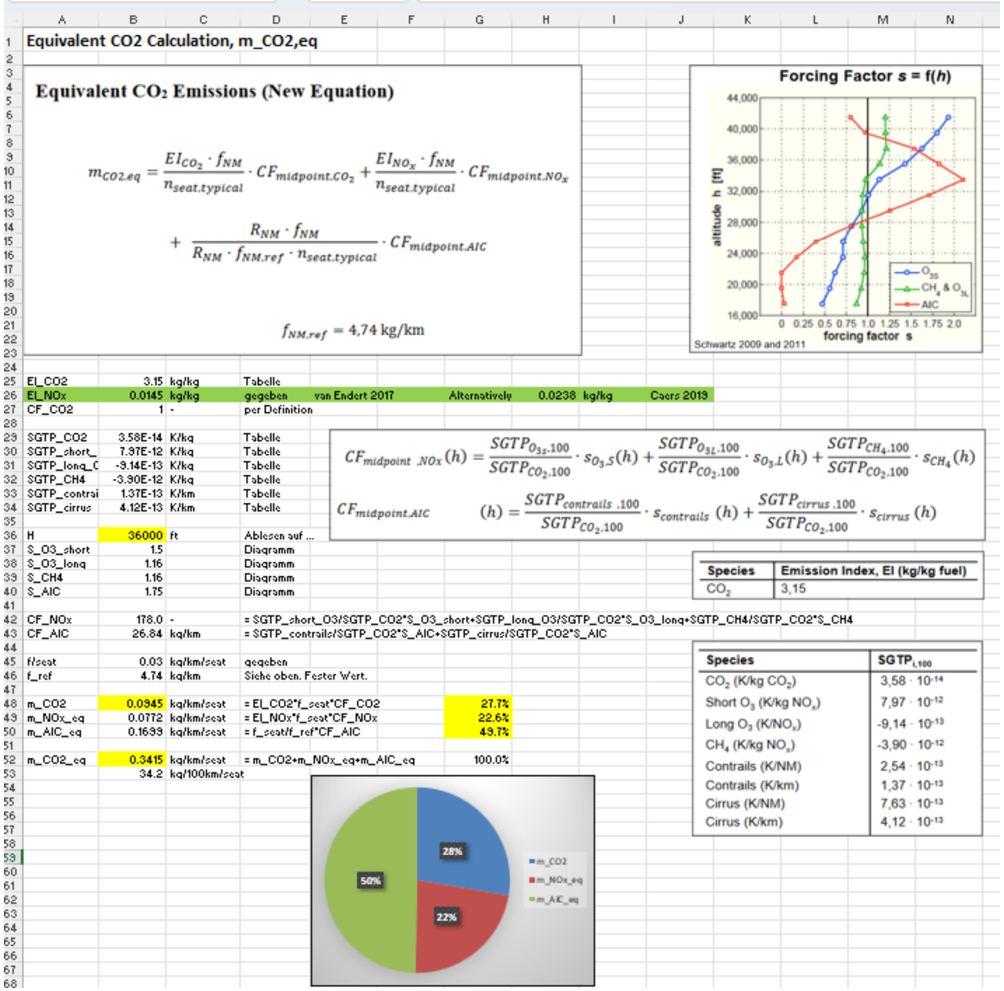
Based on KÖHLER 2008 and RÄDEL 2008.

SCHWARTZ DALLARA, Emily, 2011. *Aircraft Design for Reduced Climate Impact*. Dissertation. Stanford University. Available from: http://purl.stanford.edu/yf499mg3300

KÖHLER, Marcus O., RÄDEL, Gaby, DESSENS, Olivier, SHINE, Keith P., ROGERS, Helen L., WILD, Oliver, PYLE, John A., 2008. Impact of Perturbations to Nitrogen Oxide Emissions From Global Aviation. In: Journal of Geophysical Research, 113. Available from: https://doi.org/10.1029/2007JD009140

RÄDEL, Gaby, SHINE, Keith P., 2008. Radiative Forcing by Persistent Contrails and Its Dependence on Cruise Altitudes. In: Journal of Geophysical Research, 113. Available from: https://doi.org/10.1029/2007JD009117

Calculating Altitude-Dependent Equivalent CO2 Mass with Excel



Equivalent CO2 Calculation, m_CO2,eq

Equivalent CO₂ Emissions (New Equation)

$$m_{CO2,eq} = \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat,typical}} \cdot CF_{midpoint,CO_2} + \frac{EI_{NO_x} \cdot f_{NM}}{n_{seat,typical}} \cdot CF_{midpoint,NO_x}$$

$$+ \frac{R_{NM} \cdot f_{NM}}{R_{NM} \cdot f_{NM,ref} \cdot n_{seat,typical}} \cdot CF_{midpoint,AIC}$$

$$f_{NM,ref} = 4{,}74 \text{ kg/km}$$

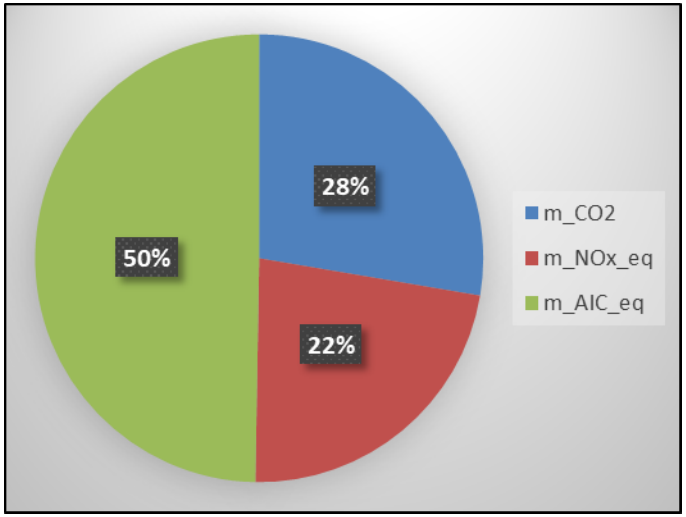
	A	B	C	D	E	F	G	H	I	J
25	EI_CO2	3.15	kg/kg	Tabelle						
26	EI_NOx	0.0145	kg/kg	gegeben	van Endert 2017		Alternatively	0.0238	kg/kg	Caers 2019
27	CF_CO2	1	-	per Definition						
28										
29	SGTP_CO2	3.58E-14	K/kg	Tabelle						
30	SGTP_short_	7.97E-12	K/kg	Tabelle						
31	SGTP_long_C	-9.14E-13	K/kg	Tabelle						
32	SGTP_CH4	-3.90E-12	K/kg	Tabelle						
33	SGTP_contrai	1.37E-13	K/km	Tabelle						
34	SGTP_cirrus	4.12E-13	K/km	Tabelle						
35										
36	H	36000	ft	Ablesen auf ...						
37	S_O3_short	1.5		Diagramm						
38	S_O3_long	1.16		Diagramm						
39	S_CH4	1.16		Diagramm						
40	S_AIC	1.75		Diagramm						
41										
42	CF_NOx	178.0	-	= SGTP_short_O3/SGTP_CO2*S_O3_short+SGTP_long_O3/SGTP_CO2*S_O3_long+SGTP_CH4/SGTP_CO2*S_CH4						
43	CF_AIC	26.84	kg/km	= SGTP_contrails/SGTP_CO2*S_AIC+SGTP_cirrus/SGTP_CO2*S_AIC						
44										
45	f/seat	0.03	kg/km/seat	gegeben						
46	f_ref	4.74	kg/km	Siehe oben. Fester Wert.						
47										
48	m_CO2	0.0945	kg/km/seat	= EI_CO2*f_seat*CF_CO2			27.7%			
49	m_NOx_eq	0.0772	kg/km/seat	= EI_NOx*f_seat*CF_NOx			22.6%			
50	m_AIC_eq	0.1699	kg/km/seat	= f_seat/f_ref*CF_AIC			49.7%			
51										
52	m_CO2_eq	0.3415	kg/km/seat	= m_CO2+m_NOx_eq+m_AIC_eq			100.0%			
53		34.2	kg/100km/seat							

$$CF_{midpoint\ ,NOx}(h) = \frac{SGTP_{O_{3S},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,S}(h) + \frac{SGTP_{O_{3L},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,L}(h) + \frac{SGTP_{CH_4,100}}{SGTP_{CO_2,100}} \cdot s_{CH_4}(h)$$

$$CF_{midpoint,AIC}\ (h) = \frac{SGTP_{contrails\ ,100}}{SGTP_{CO_2,100}} \cdot s_{contrails}\ (h) + \frac{SGTP_{cirrus\ ,100}}{SGTP_{CO_2,100}} \cdot s_{cirrus}\ (h)$$

Species	Emission Index, EI (kg/kg fuel)
CO_2	3,15

Species	$SGTP_{i,100}$
CO_2 (K/kg CO_2)	$3{,}58 \cdot 10^{-14}$
Short O_3 (K/kg NO_x)	$7{,}97 \cdot 10^{-12}$
Long O_3 (K/NO_x)	$-9{,}14 \cdot 10^{-13}$
CH_4 (K/kg NO_x)	$-3{,}90 \cdot 10^{-12}$
Contrails (K/NM)	$2{,}54 \cdot 10^{-13}$
Contrails (K/km)	$1{,}37 \cdot 10^{-13}$
Cirrus (K/NM)	$7{,}63 \cdot 10^{-13}$
Cirrus (K/km)	$4{,}12 \cdot 10^{-13}$



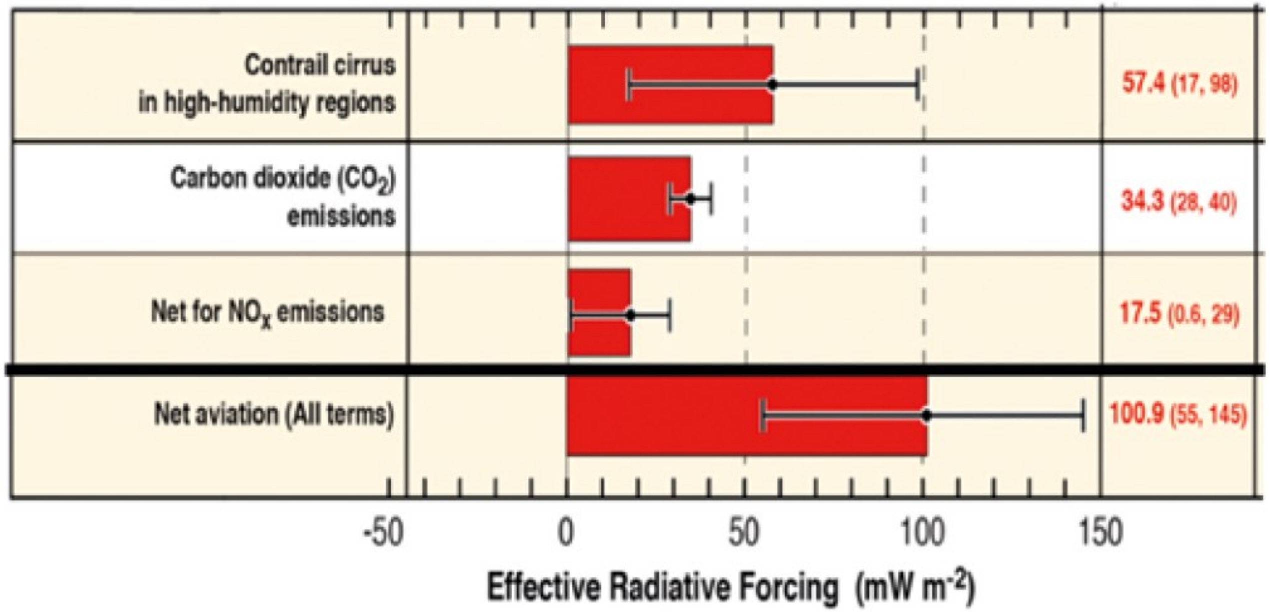
EI_NOx = 0.0145 kg/kg

h = 36000 ft

Standard split of CO2,eq:

1/6 = 1/6 = 16.7% from NOx
2/6 = 1/3 = 33.3% from CO2
3/6 = 1/2 = 50.0% from AIC

Relative Contributions to Global Warming

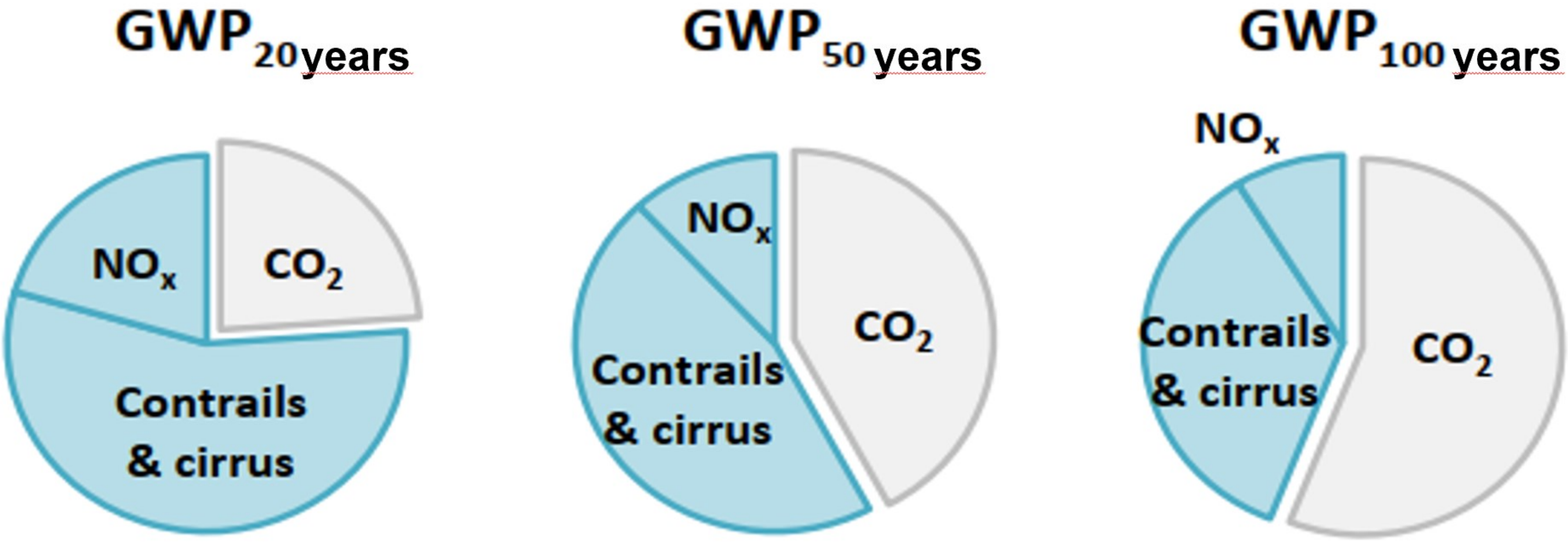


LEE, D.S., et al., 2020. The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018. In: Atmospheric Environment, vol. 211 (2021), art. 17834. Available from: https://doi.org/10.1016/j.atmosenv.2020.117834

This can be compared to equivalent CO2 at peak AIC ("33548 ft") according to the model by SCHWARTZ 2009 due to

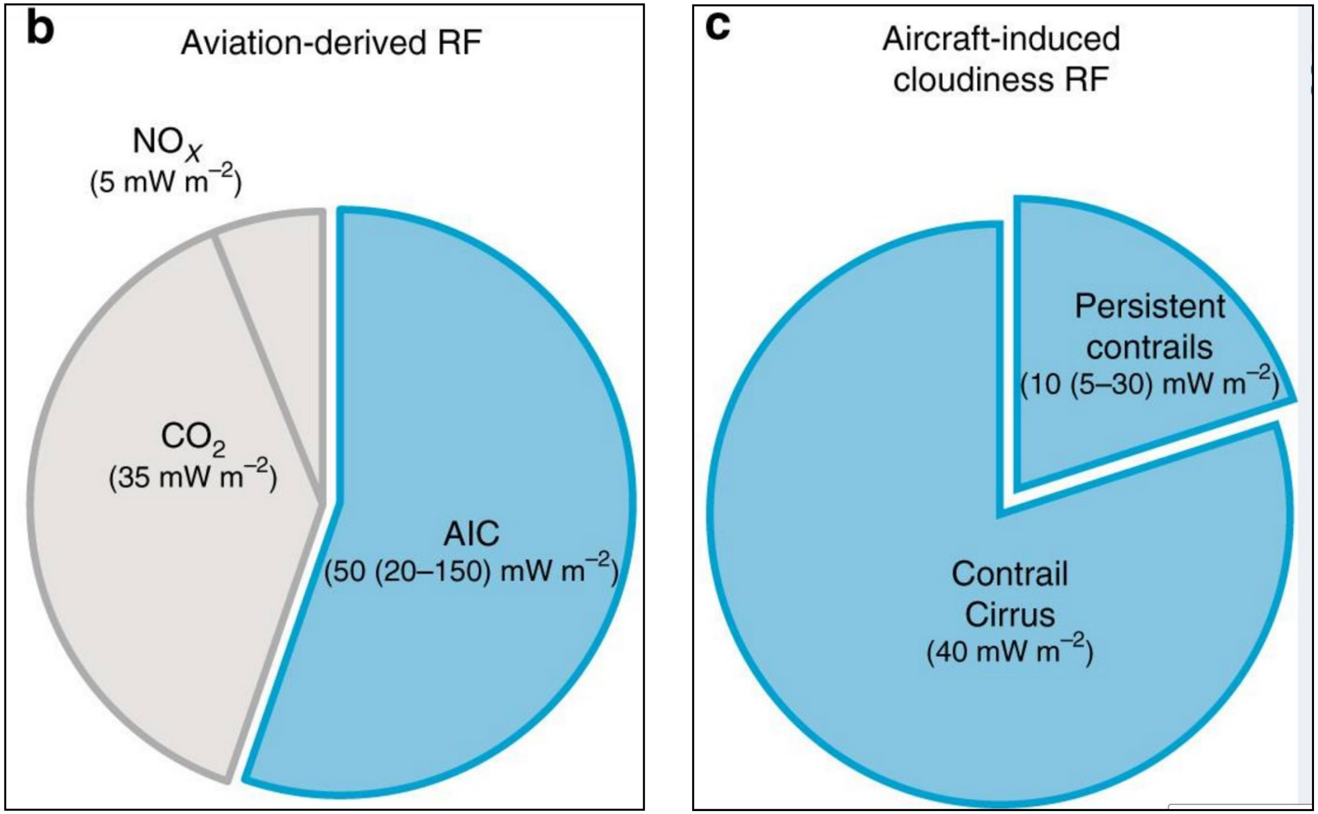
- 54.7% AIC
- 23.6% CO2
- 21.7% NOX

Aviation-Induced Cloudiness (AIC) –
Share Depends on Integration Time



LEEMÜLLER, 2022. Climate Optimized Flight Routes – The Path from Research to Operations. Hamburg Aerospace Lecture Series (DGLR, RAeS, VDI, ZAL, HAW Hamburg), Hamburg, Germany, 2022-11-24. Zenodo. https://doi.org/10.5281/zenodo.7396325

Aviation-Induced Cloudiness: Contrail Cirrus & Persistent Contrails

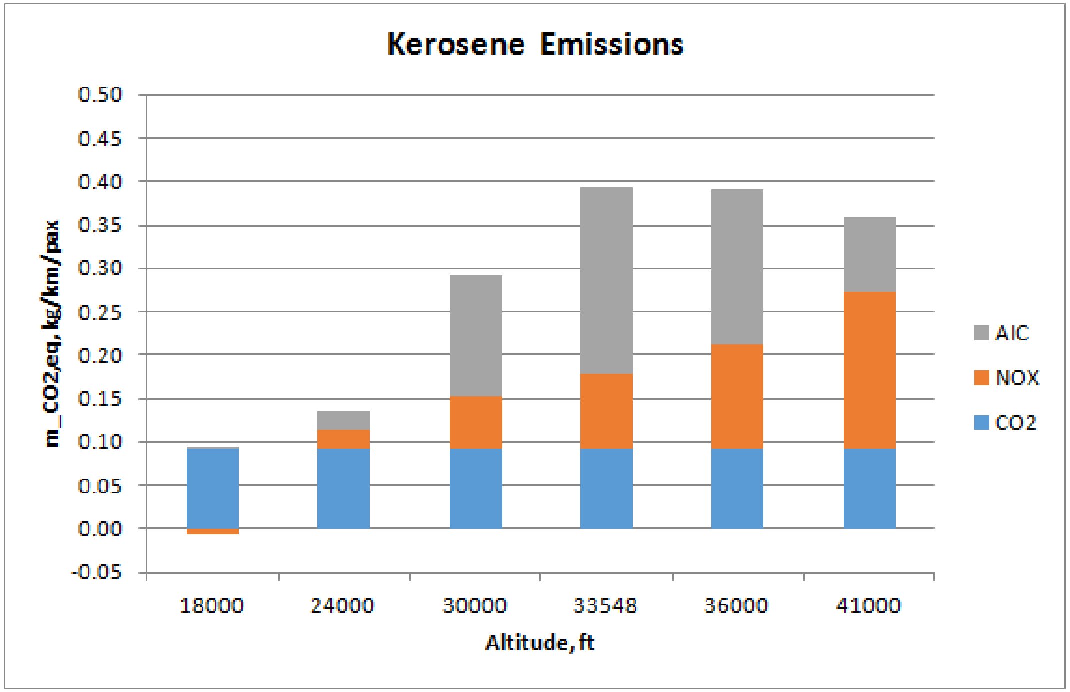


Cirrus/Contrails = 4.0

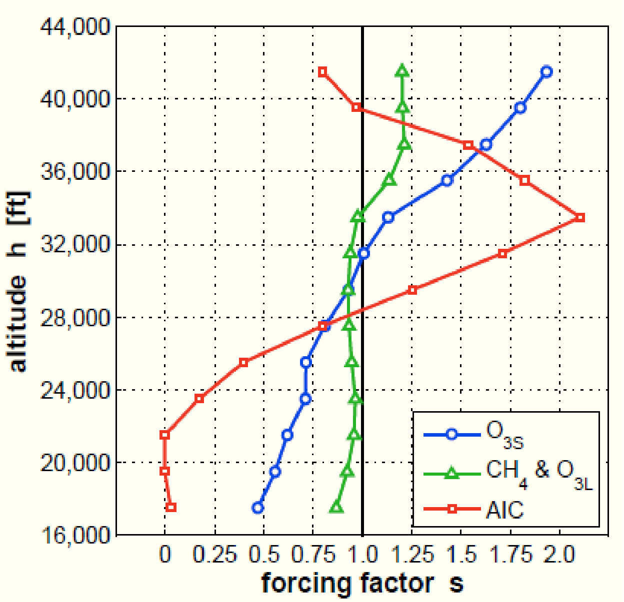
(b) Aviation forcing components, of which aviation-induced cloudiness (AIC) account for more than half.
(c) Breakdown of AIC radiative forcing into contrail cirrus and persistent contrails.

KÄRCHER, Bernd, 2018. Formation and Radiative Forcing of Contrail Cirrus. In: *Nature Communications*, vol. 9, art. 1824. Available from: https://doi.org/10.1038/s41467-018-04068-0

Calculating Altitude-Dependent Equivalent CO2 Mass



https://doi.org/10.7910/DVN/DLJUUK



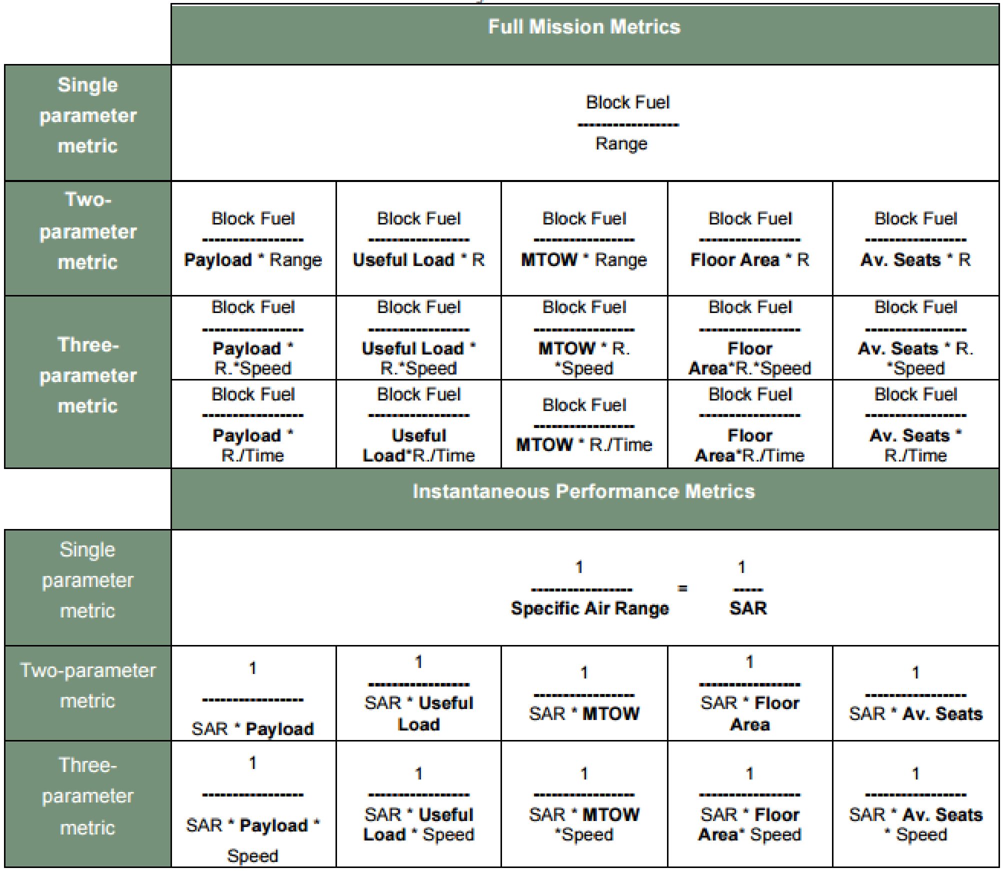
SCHWARTZ 2009 and 2011

- At **41000 ft**, AIC is low. Equivalent CO2 is now dominated by NOx.
- Equivalent CO2 mass peaks at **"peak AIC" (33548 ft)** due to contrails and contrail cirrus.
- At lower altitudes (**24000 ft**) very little equivalent CO2 is produced. NOx effects and AIC are low. CO2 dominates.
- At very low altitudes (**18000 ft**) the forcing factor for CH4 and O3L is getting so large that it dominates the forcing factor of the warming O3S. NOx is now **slightly cooling**.

Aircraft Fuel Consumption

Fuel Consumption

Table 1: Summary of candidate metrics



	Full Mission Metrics				
Single parameter metric	$\frac{\text{Block Fuel}}{\text{Range}}$				
Two-parameter metric	$\frac{\text{Block Fuel}}{\textbf{Payload}\text{ * Range}}$	$\frac{\text{Block Fuel}}{\textbf{Useful Load}\text{ * R}}$	$\frac{\text{Block Fuel}}{\textbf{MTOW}\text{ * Range}}$	$\frac{\text{Block Fuel}}{\textbf{Floor Area}\text{ * R}}$	$\frac{\text{Block Fuel}}{\textbf{Av. Seats}\text{ * R}}$
Three-parameter metric	$\frac{\text{Block Fuel}}{\textbf{Payload}\text{ * R.*Speed}}$	$\frac{\text{Block Fuel}}{\textbf{Useful Load}\text{ * R.*Speed}}$	$\frac{\text{Block Fuel}}{\textbf{MTOW}\text{ * R. *Speed}}$	$\frac{\text{Block Fuel}}{\textbf{Floor Area}\text{*R.*Speed}}$	$\frac{\text{Block Fuel}}{\textbf{Av. Seats}\text{ * R. *Speed}}$
	$\frac{\text{Block Fuel}}{\textbf{Payload}\text{ * R./Time}}$	$\frac{\text{Block Fuel}}{\textbf{Useful Load}\text{*R./Time}}$	$\frac{\text{Block Fuel}}{\textbf{MTOW}\text{ * R./Time}}$	$\frac{\text{Block Fuel}}{\textbf{Floor Area}\text{*R./Time}}$	$\frac{\text{Block Fuel}}{\textbf{Av. Seats}\text{ * R./Time}}$
	Instantaneous Performance Metrics				
Single parameter metric	$\frac{1}{\textbf{Specific Air Range}} = \frac{1}{\textbf{SAR}}$				
Two-parameter metric	$\frac{1}{\text{SAR * }\textbf{Payload}}$	$\frac{1}{\text{SAR * }\textbf{Useful Load}}$	$\frac{1}{\text{SAR * }\textbf{MTOW}}$	$\frac{1}{\text{SAR * }\textbf{Floor Area}}$	$\frac{1}{\text{SAR * }\textbf{Av. Seats}}$
Three-parameter metric	$\frac{1}{\text{SAR * }\textbf{Payload}\text{ * Speed}}$	$\frac{1}{\text{SAR * }\textbf{Useful Load}\text{ * Speed}}$	$\frac{1}{\text{SAR * }\textbf{MTOW}\text{ *Speed}}$	$\frac{1}{\text{SAR * }\textbf{Floor Area}\text{* Speed}}$	$\frac{1}{\text{SAR * }\textbf{Av. Seats}\text{ * Speed}}$

Note: R = Range

http://partner.mit.edu/projects/metrics-aviation-co2-standard

PARTNER

Partnership for Air Transportation Noise and Emissions Reduction

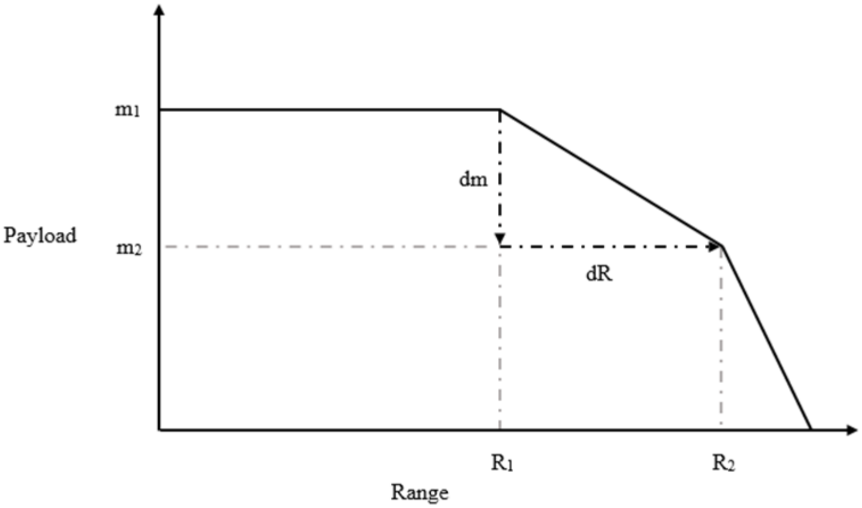
Selecting a Fuel Metric:

$1/(SAR \cdot n_{seat})$

Fuel Consumption – From Payload-Range Diagram

Here taken from:

Payload-Range-Diagram available from: "Documents for Airport Planning"

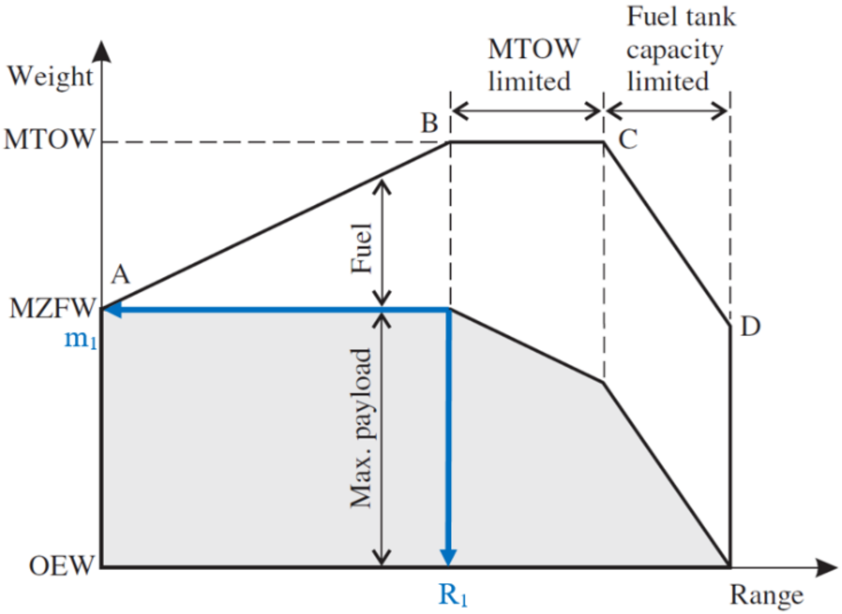


See: http://links.ProfScholz.de

$$SAR = -\frac{dR}{dm}$$

$$\boxed{SAR = \frac{R_2 - R_1}{m_1 - m_2}}$$

Fuel Consumption – From Extended Payload-Range Diagram



$$SAR = -\frac{dR}{dm}$$

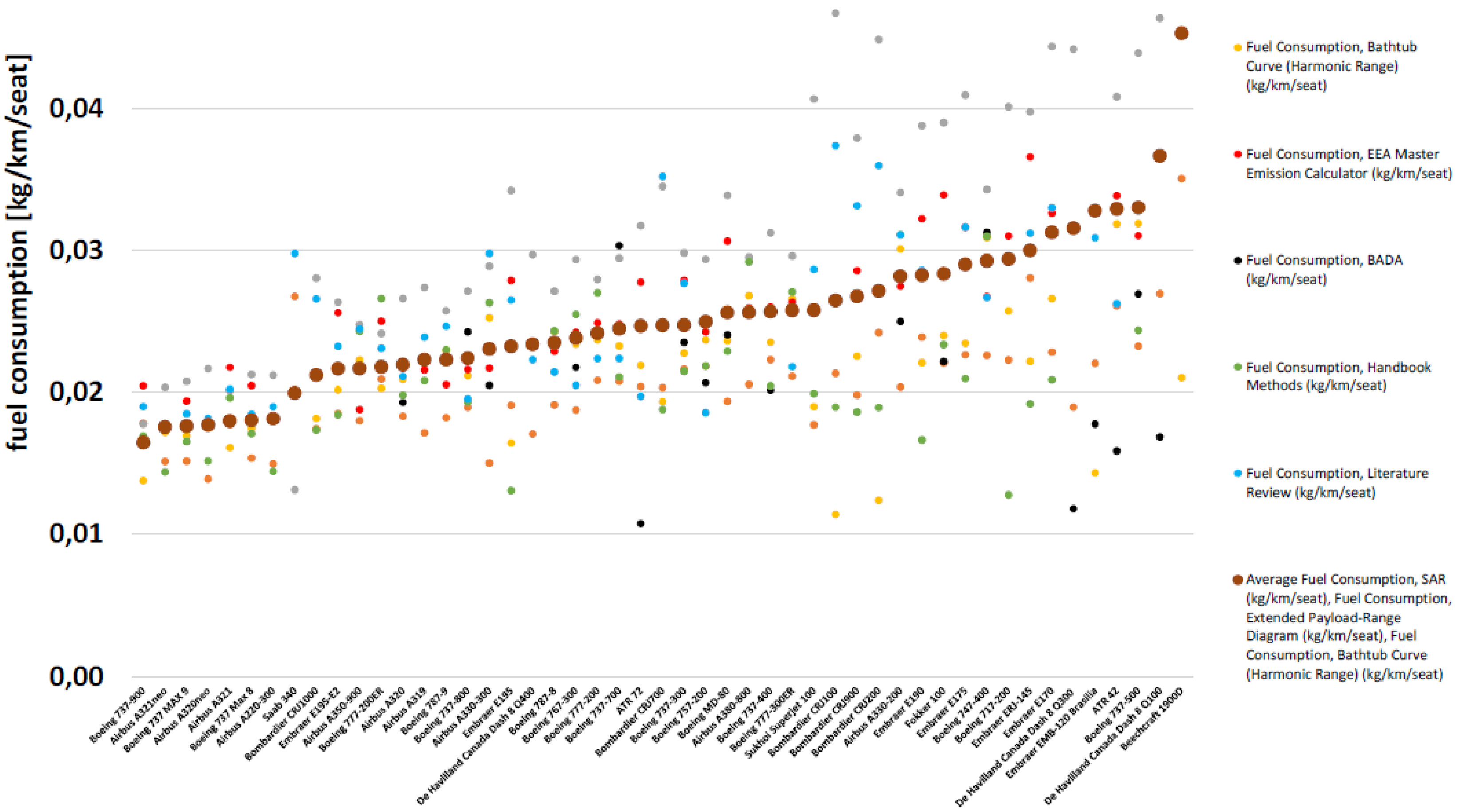
$$SAR = \frac{MTOW - MZFW}{R_1}$$

Consumption = (MTOW – MZFW) / (R_1 · n_{seats}) · 100

Example Airbus A320neo:
2.2 kg per 100 km and seat = (73500 kg – 62800 kg) / (3180 km · 150) · 100

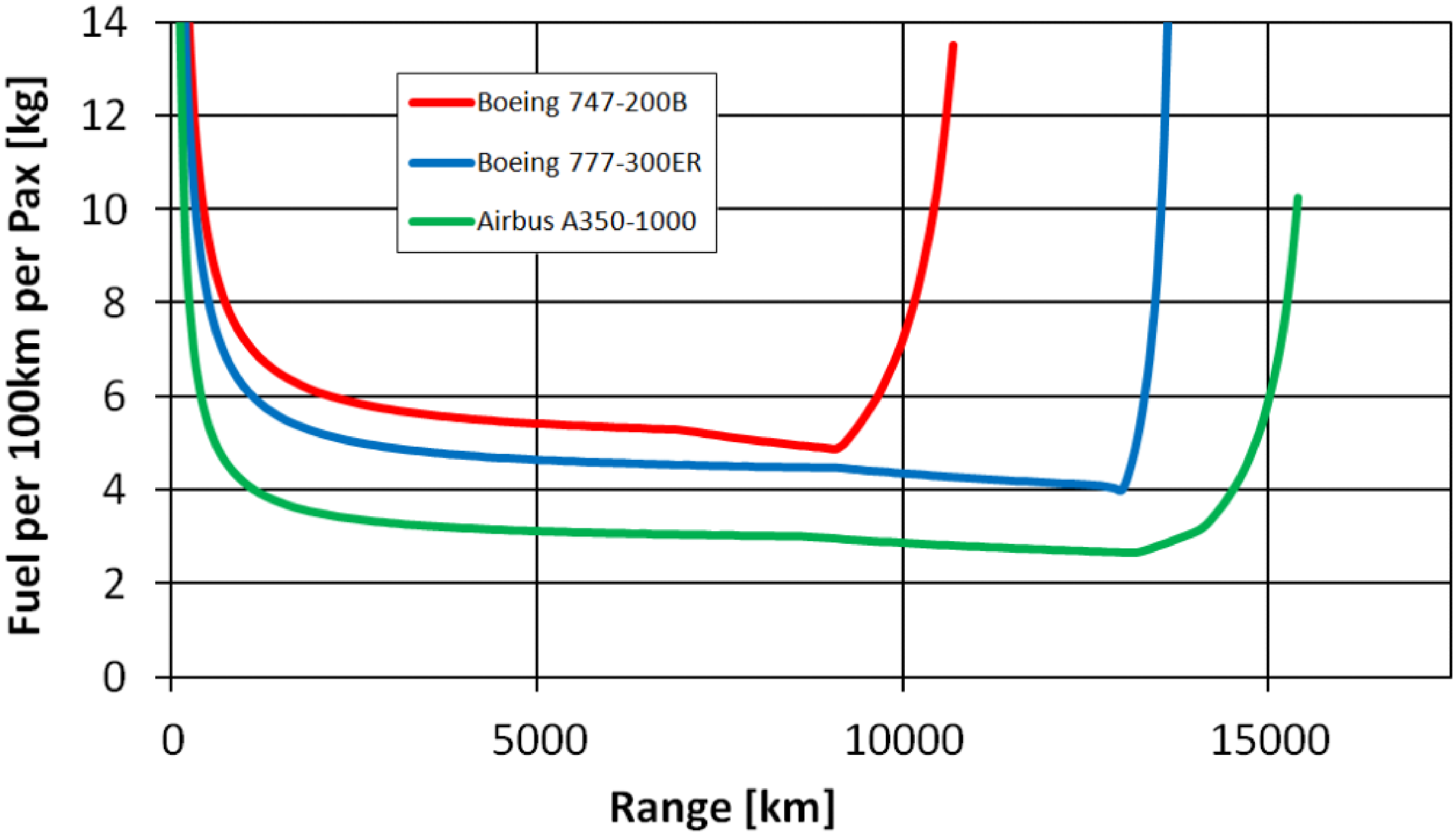
Kerosene: 0.8 kg/liter
2.75 liter per 100 km and seat

Fuel Consumption Comparison – 8 Methods, 50 Aircraft



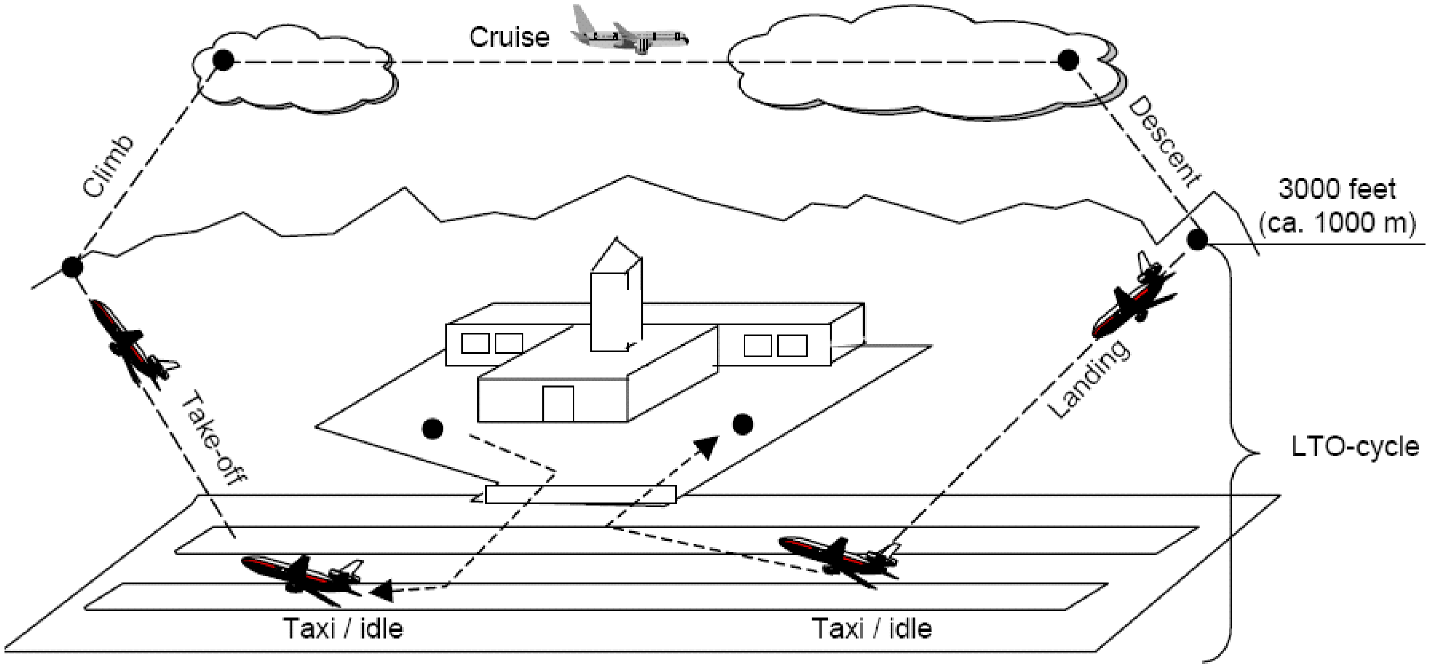
KÜHN, Marius, 2023. Fuel Consumption of the 50 Most Used Passenger Aircraft. Available from:
https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2023-09-11.011

Fuel Consumption Comparison – Bathtub Curve



Local Air Pollution at Airports

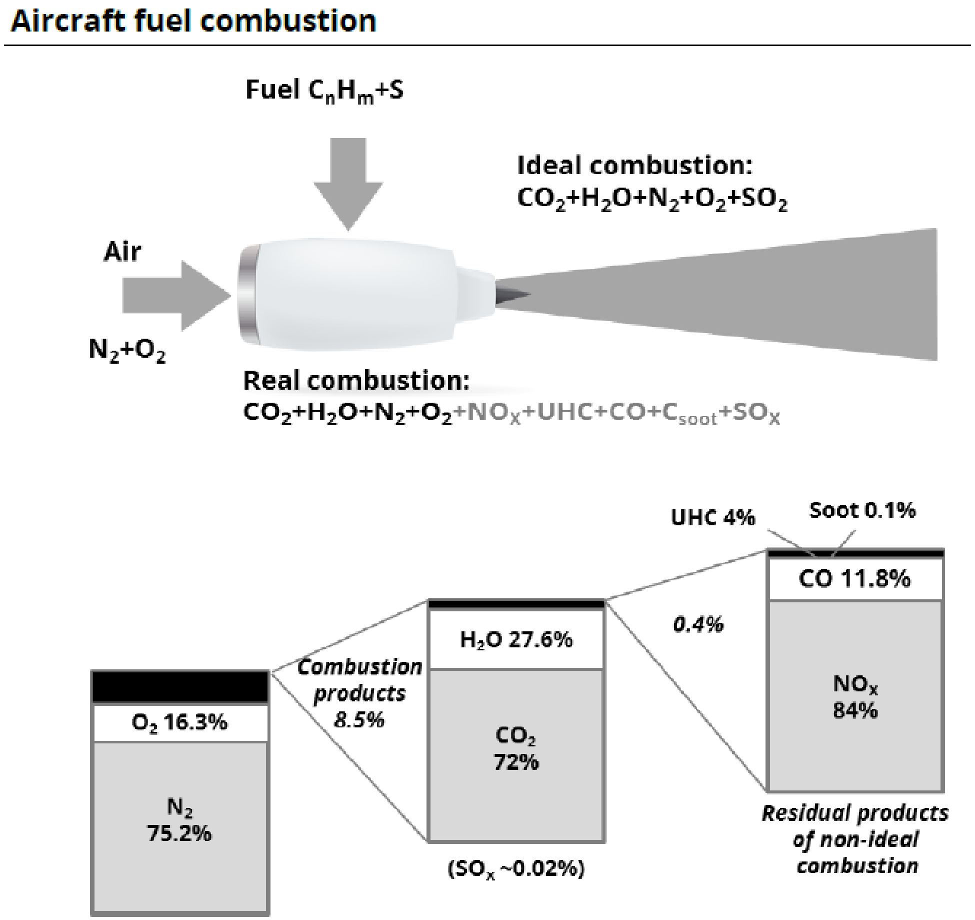
Landing and Take-Off Cycle (LTO)



Definition of the landing and take-off cycle (LTO)

http://www.eea.europa.eu/publications/emep-eea-guidebook-2016

Fuel Combustion

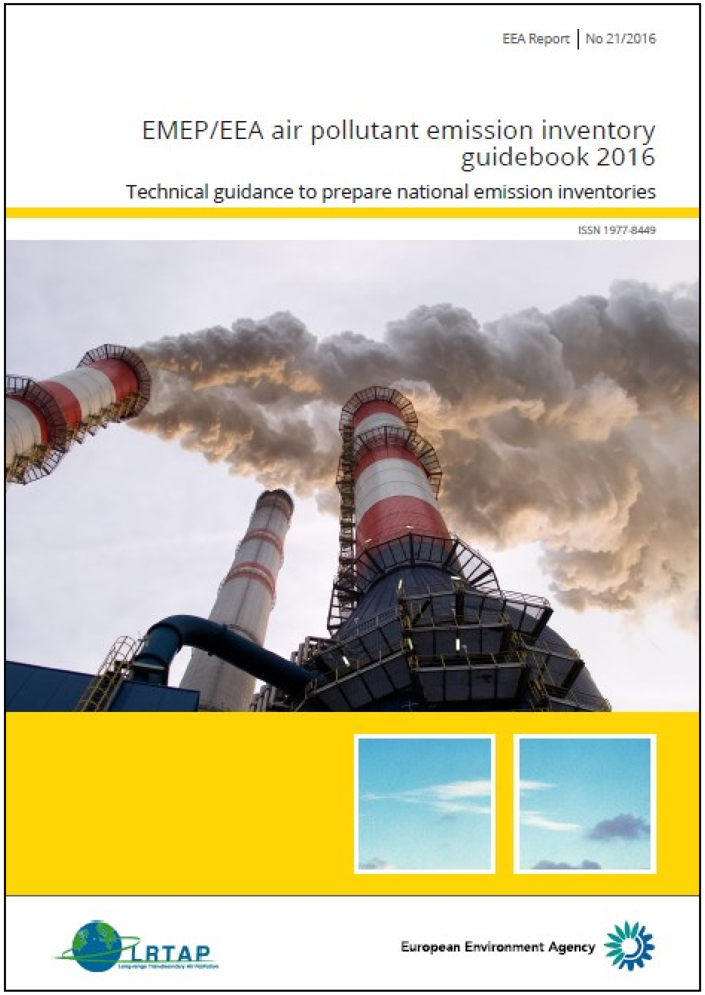


Species	Emission Index (kg/kg fuel)
CO_2	3,16
H_2O	1,23
SO_2	$2{,}00 \cdot 10^{-4}$
Soot	$4{,}00 \cdot 10^{-5}$

http://www.ipcc.ch/ipccreports/sres/aviation

http://www.eea.europa.eu/publications/emep-eea-guidebook-2016

Data Source



EEA Report | No 21/2016

EMEP/EEA air pollutant emission inventory guidebook 2016

Technical guidance to prepare national emission inventories

ISSN 1977-8449

LRTAP

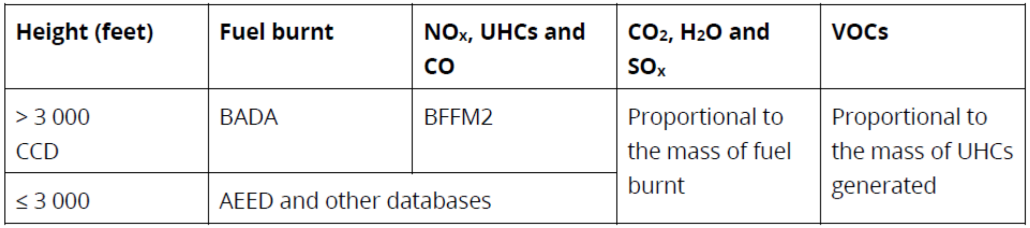
European Environment Agency

European Environment Agency

European Monitoring and Evaluation Program (EMEP)
http://www.emep.int

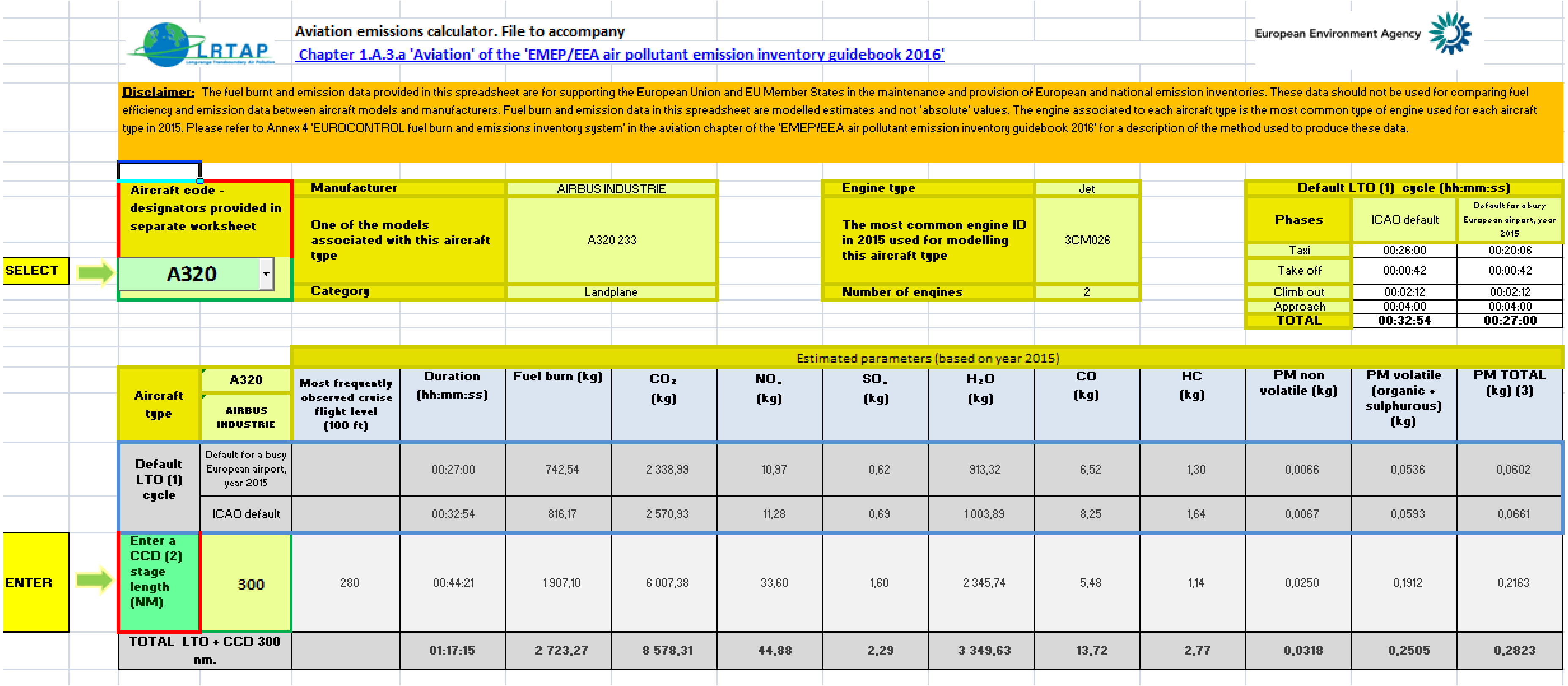
European Environment Agency
http://www.eea.europa.eu/publications/emep-eea-guidebook-2016

Users will find two Excel files:
- Master emission calculator
- LTO emission calculator



Height (feet)	**Fuel burnt**	**NO_x, UHCs and CO**	**CO_2, H_2O and SO_x**	**VOCs**
> 3 000 CCD	BADA	BFFM2	Proportional to the mass of fuel burnt	Proportional to the mass of UHCs generated
≤ 3 000	AEED and other databases			

Global Warming



Aviation emissions calculator. File to accompany

Chapter 1.A.3.a 'Aviation' of the 'EMEP/EEA air pollutant emission inventory guidebook 2016'

Disclaimer: The fuel burnt and emission data provided in this spreadsheet are for supporting the European Union and EU Member States in the maintenance and provision of European and national emission inventories. These data should not be used for comparing fuel efficiency and emission data between aircraft models and manufacturers. Fuel burn and emission data in this spreadsheet are modelled estimates and not 'absolute' values. The engine associated to each aircraft type is the most common type of engine used for each aircraft type in 2015. Please refer to Annex 4 'EUROCONTROL fuel burn and emissions inventory system' in the aviation chapter of the 'EMEP/EEA air pollutant emission inventory guidebook 2016' for a description of the method used to produce these data.

Aircraft code - designators provided in separate worksheet

SELECT → A320

Manufacturer	AIRBUS INDUSTRIE
One of the models associated with this aircraft type	A320 233
Category	Landplane

Engine type	Jet
The most common engine ID in 2015 used for modelling this aircraft type	3CM026
Number of engines	2

Default LTO (1) cycle (hh:mm:ss)

Phases	ICAO default	Default for a busy European airport, year 2015
Taxi	00:26:00	00:20:06
Take off	00:00:42	00:00:42
Climb out	00:02:12	00:02:12
Approach	00:04:00	00:04:00
TOTAL	**00:32:54**	**00:27:00**

Estimated parameters (based on year 2015)

Aircraft type	**A320** **AIRBUS INDUSTRIE**	**Most frequently observed cruise flight level (100 ft)**	**Duration (hh:mm:ss)**	**Fuel burn (kg)**	**CO_2 (kg)**	**NO_x (kg)**	**SO_x (kg)**	**H_2O (kg)**	**CO (kg)**	**HC (kg)**	**PM non volatile (kg)**	**PM volatile (organic + sulphurous) (kg)**	**PM TOTAL (kg) (3)**
Default LTO (1) cycle	Default for a busy European airport, year 2015		00:27:00	742,54	2 338,99	10,97	0,62	913,32	6,52	1,30	0,0066	0,0536	0,0602
	ICAO default		00:32:54	816,17	2 570,93	11,28	0,69	1 003,89	8,25	1,64	0,0067	0,0593	0,0661
Enter a CCD (2) stage length (NM)	300	280	00:44:21	1 907,10	6 007,38	33,60	1,60	2 345,74	5,48	1,14	0,0250	0,1912	0,2163
TOTAL LTO + CCD 300 nm.			**01:17:15**	**2 723,27**	**8 578,31**	**44,88**	**2,29**	**3 349,63**	**13,72**	**2,77**	**0,0318**	**0,2505**	**0,2823**

ENTER →

Local Air Pollution

Characterization factors of ReCiPe

Midpoint category	NO_x	SO_2	PM	CO	HC
Photochemical oxidant formation (ozone)	1	0,081	-	0,046	0,476
Particulate matter formation	0,22	0,20	1	-	-

... more details ...

Ozone :

$$NMVOC_{LTO} = 1 \cdot (NO_x)_{LTO} + 0{,}081 \cdot (SO_2)_{LTO} + 0{,}046 \cdot (CO)_{LTO} + 0{,}476 \cdot (HC)_{LTO}$$

PM :

$$(PM_{equivalents})_{LTO} = 0{,}22 \cdot (NO_x)_{LTO} + 0{,}20 \cdot (SO_2)_{LTO} + 1 \cdot (PM)_{LTO}$$

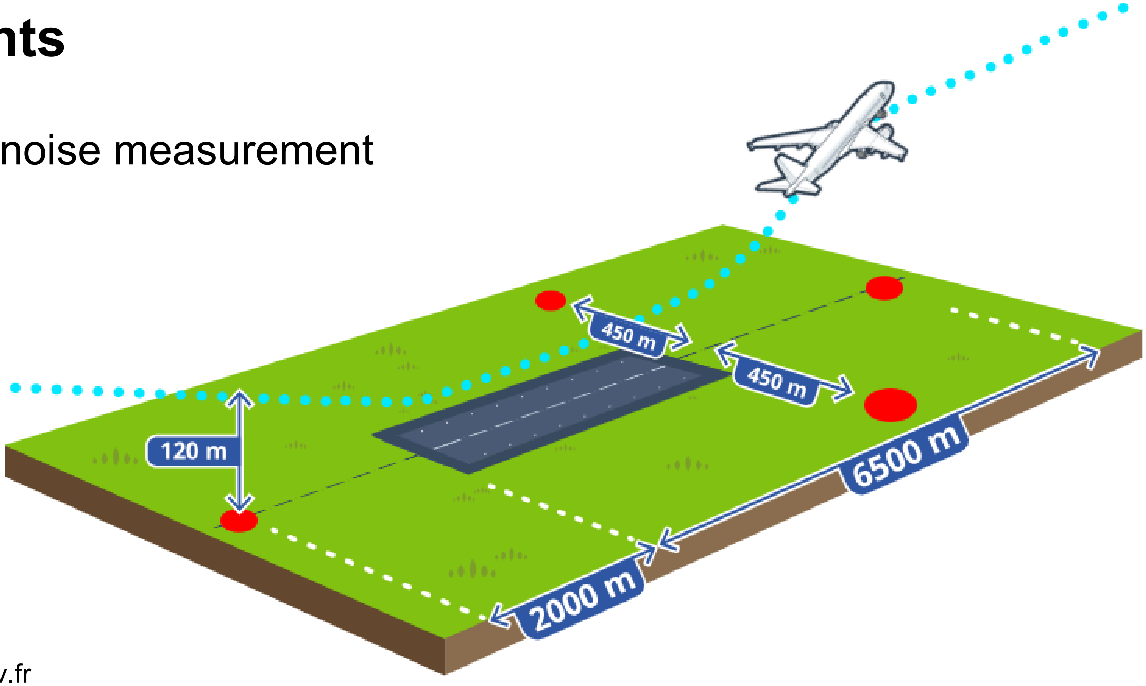
$(PM)_{LTO}$ calculated from "smoke number"

But: Only NOx enters the overall rating for the Ecolabel

Noise at Airports

Noise Measurements

Reference points for the noise measurement



https://noisedb.stac.aviation-civile.gouv.fr

Approach

An approach point located at a distance of 2000 meters from the runway threshold to the landing

Lateral (takeoff at maximum power)

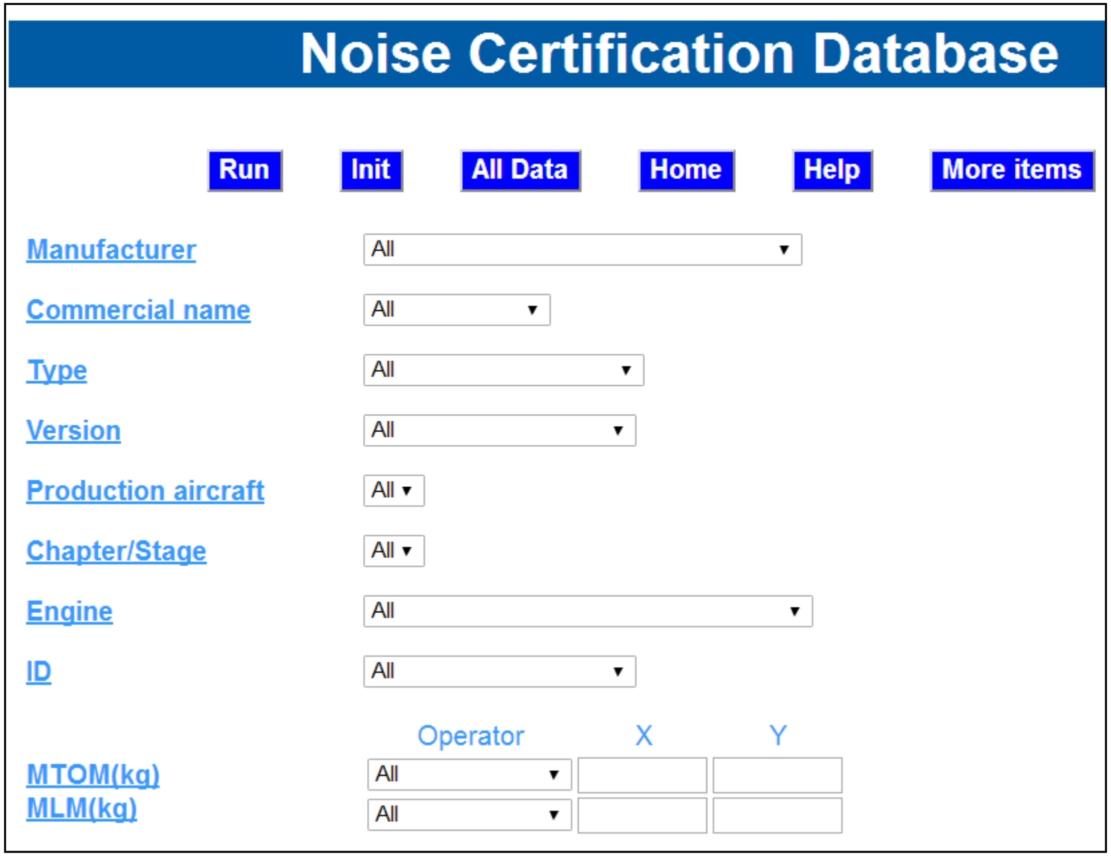
Two lateral points located at 450(*) meters on each side of the centreline of the runway where the take-off noise level is maximum. The certified noise level is the average of the noise levels observed at these two measurement points.

(*) 650 meters for Chapter 2

Flyover (Takeoff after power reduction)

A flyover point located on the centerline of the runway at a distance of 6500 meters from the brake release.

Noise Database



Noise Certification Database

Run | Init | All Data | Home | Help | More items

Manufacturer: All ▾

Commercial name: All ▾

Type: All ▾

Version: All ▾

Production aircraft: All ▾

Chapter/Stage: All ▾

Engine: All ▾

ID: All ▾

	Operator	X	Y
MTOM(kg)	All ▾		
MLM(kg)	All ▾		

https://noisedb.stac.aviation-civile.gouv.fr

ICAO · OACI · ИКАО

dgac

Noise Certification Database

$$NIV_{lateral} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{\text{lateral}}$$

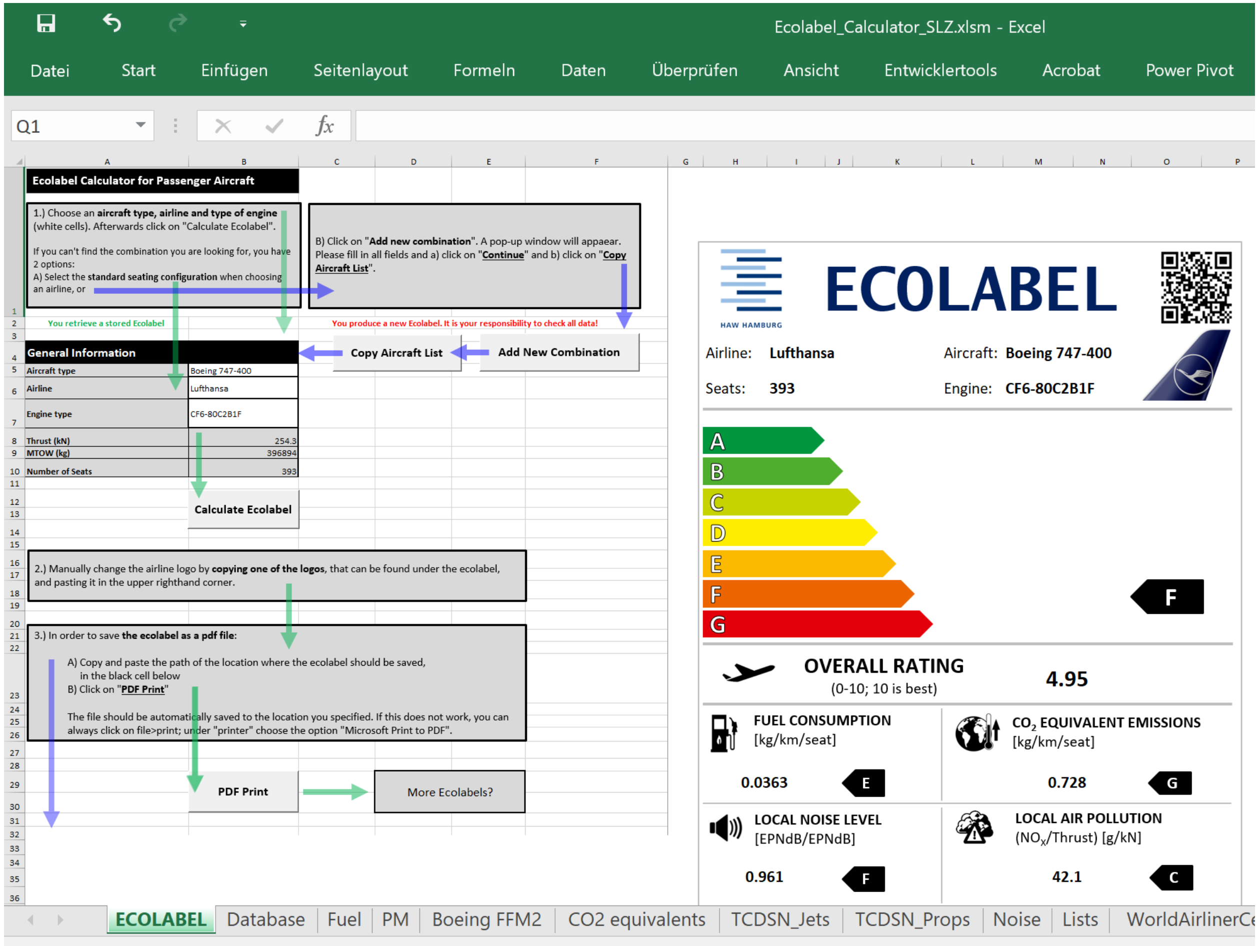
$$NIV_{flyover} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{\text{flyover}}$$

$$NIV_{approach} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{\text{approach}}$$

$$NIV_{average} = \frac{NIV_{lateral} + NIV_{flyover} + NIV_{approach}}{3}$$

Ecolabels for Aircraft

Ecolabel Calculator (the main tool)



Ecolabel Calculator for Passenger Aircraft

1.) Choose an **aircraft type, airline and type of engine** (white cells). Afterwards click on "Calculate Ecolabel".

If you can't find the combination you are looking for, you have 2 options:
A) Select the **standard seating configuration** when choosing an airline, or

B) Click on "**Add new combination**". A pop-up window will appaear. Please fill in all fields and a) click on "**Continue**" and b) click on "**Copy Aircraft List**".

You retrieve a stored Ecolabel

You produce a new Ecolabel. It is your responsibility to check all data!

General Information	
Aircraft type	Boeing 747-400
Airline	Lufthansa
Engine type	CF6-80C2B1F
Thrust (kN)	254.3
MTOW (kg)	396894
Number of Seats	393

2.) Manually change the airline logo by **copying one of the logos**, that can be found under the ecolabel, and pasting it in the upper righthand corner.

3.) In order to save **the ecolabel as a pdf file**:

A) Copy and paste the path of the location where the ecolabel should be saved, in the black cell below
B) Click on "**PDF Print**"

The file should be automatically saved to the location you specified. If this does not work, you can always click on file>print; under "printer" choose the option "Microsoft Print to PDF".

ECOLABEL

Airline: **Lufthansa**
Aircraft: **Boeing 747-400**
Seats: **393**
Engine: **CF6-80C2B1F**

F

OVERALL RATING (0-10; 10 is best) **4.95**

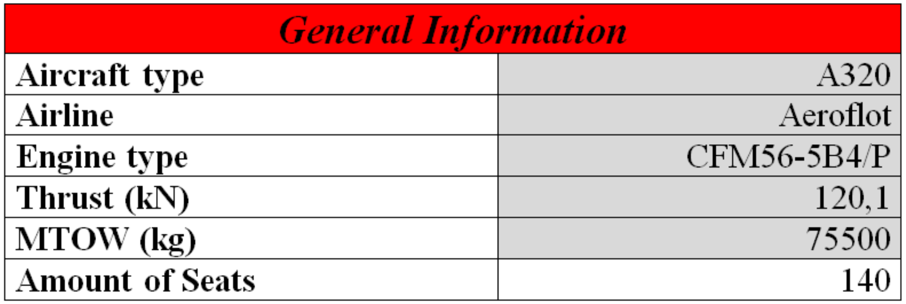
FUEL CONSUMPTION [kg/km/seat]: 0.0363 **E**

CO$_2$ EQUIVALENT EMISSIONS [kg/km/seat]: 0.728 **G**

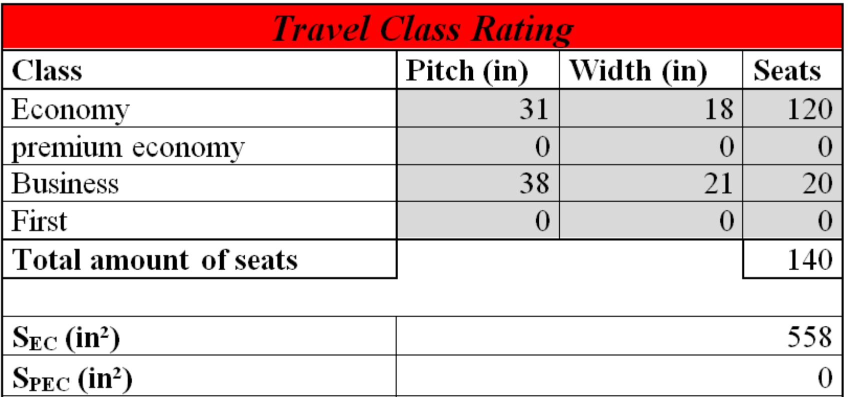
LOCAL NOISE LEVEL [EPNdB/EPNdB]: 0.961 **F**

LOCAL AIR POLLUTION (NO$_x$/Thrust) [g/kN]: 42.1 **C**

Ecolabel Calculator (simple beginnings)



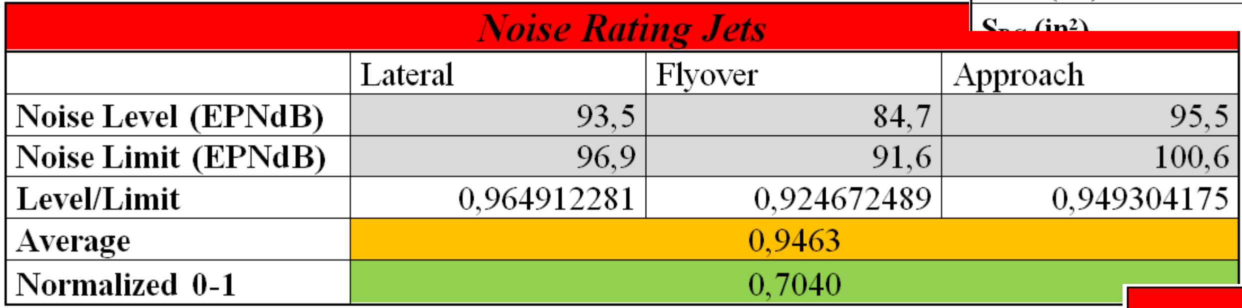
General Information	
Aircraft type	A320
Airline	Aeroflot
Engine type	CFM56-5B4/P
Thrust (kN)	120,1
MTOW (kg)	75500
Amount of Seats	140



Travel Class Rating

Class	Pitch (in)	Width (in)	Seats
Economy	31	18	120
premium economy	0	0	0
Business	38	21	20
First	0	0	0
Total amount of seats			140
S_{EC} (in²)			558
S_{PEC} (in²)			0
[illegible] (in²)			798

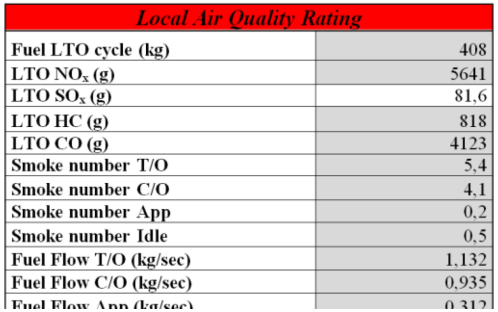
... more details ...



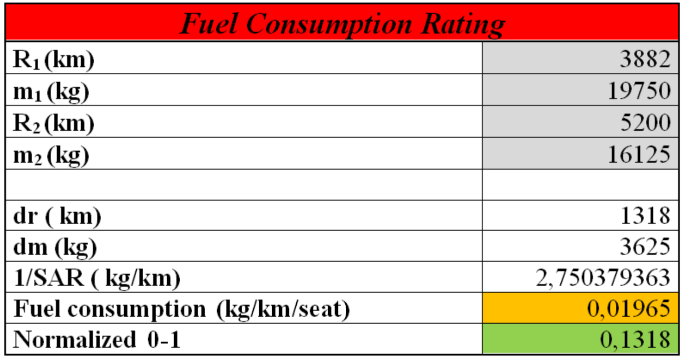
Noise Rating Jets

	Lateral	Flyover	Approach
Noise Level (EPNdB)	93,5	84,7	95,5
Noise Limit (EPNdB)	96,9	91,6	100,6
Level/Limit	0,964912281	0,924672489	0,949304175
Average	0,9463		
Normalized 0-1	0,7040		

... more details ...



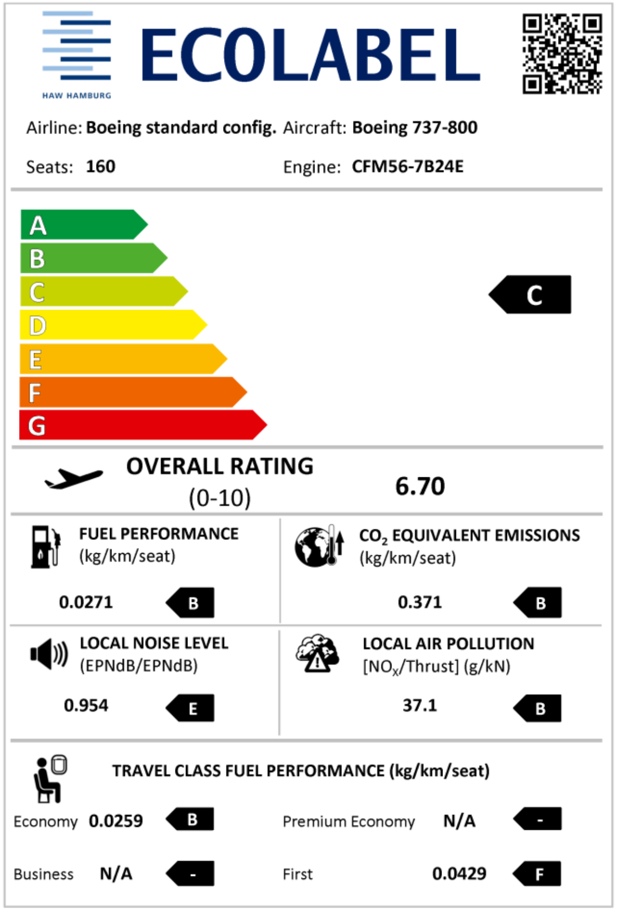
Local Air Quality Rating	
Fuel LTO cycle (kg)	408
LTO NO_x (g)	5641
LTO SO_x (g)	81,6
LTO HC (g)	818
LTO CO (g)	4123
Smoke number T/O	5,4
Smoke number C/O	4,1
Smoke number App	0,2
Smoke number Idle	0,5
Fuel Flow T/O (kg/sec)	1,132
Fuel Flow C/O (kg/sec)	0,935
Fuel Flow App (kg/sec)	0,312



Fuel Consumption Rating	
R_1 (km)	3882
m_1 (kg)	19750
R_2 (km)	5200
m_2 (kg)	16125
dr (km)	1318
dm (kg)	3625
1/SAR (kg/km)	2,750379363
Fuel consumption (kg/km/seat)	0,01965
Normalized 0-1	0,1318

Ecolabel for Aircraft

Boeing 737 Family vs. Airbus A320 Family



HAW HAMBURG

ECOLABEL

Airline: **Boeing standard config.** Aircraft: **Boeing 737-800**

Seats: **160** Engine: **CFM56-7B24E**

A
B
C
D
E
F
G

C

OVERALL RATING (0-10) **6.70**

FUEL PERFORMANCE (kg/km/seat) **0.0271** **B**

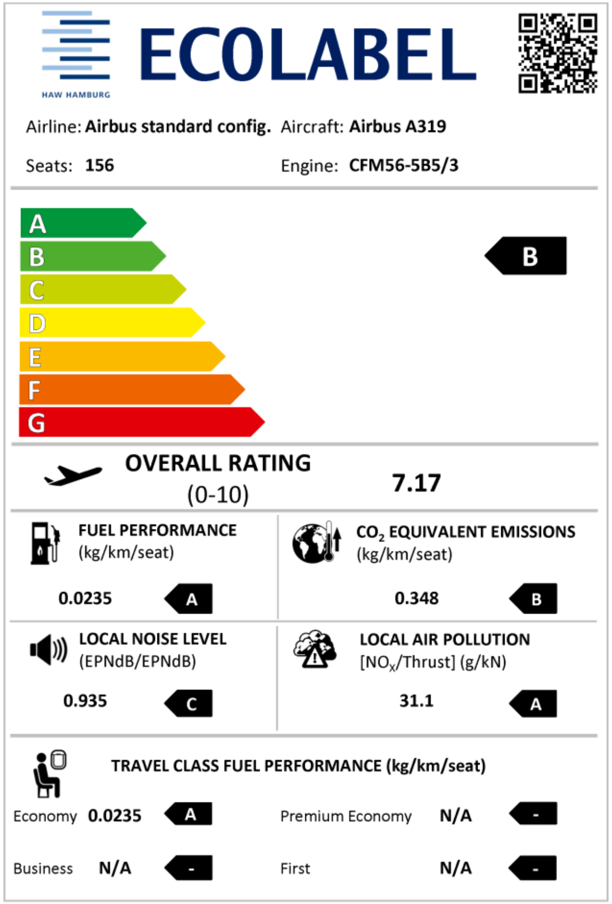
CO_2 EQUIVALENT EMISSIONS (kg/km/seat) **0.371** **B**

LOCAL NOISE LEVEL (EPNdB/EPNdB) **0.954** **E**

LOCAL AIR POLLUTION [NO_x/Thrust] (g/kN) **37.1** **B**

TRAVEL CLASS FUEL PERFORMANCE (kg/km/seat)

Economy **0.0259** **B**
Premium Economy **N/A** **-**
Business **N/A** **-**
First **0.0429** **F**



HAW HAMBURG

ECOLABEL

Airline: **Airbus standard config.** Aircraft: **Airbus A319**

Seats: **156** Engine: **CFM56-5B5/3**

A
B
C
D
E
F
G

B

OVERALL RATING (0-10) **7.17**

FUEL PERFORMANCE (kg/km/seat) **0.0235** **A**

CO_2 EQUIVALENT EMISSIONS (kg/km/seat) **0.348** **B**

LOCAL NOISE LEVEL (EPNdB/EPNdB) **0.935** **C**

LOCAL AIR POLLUTION [NO_x/Thrust] (g/kN) **31.1** **A**

TRAVEL CLASS FUEL PERFORMANCE (kg/km/seat)

Economy **0.0235** **A**
Premium Economy **N/A** **-**
Business **N/A** **-**
First **N/A** **-**

New Technologies

Calculating Maximum Range for Battery–Electric Flight

e_{bat} : specific energy
E_{bat} : energy in battery
E : glide ratio (aerodynamic efficiency)
L : lift
D : drag
W: weight
V : flight speed
R : range
t: time
g : earth acceleration
P : power
η : efficiency (prop : propeller)

$$e_{bat} = \frac{E_{bat}}{m_{bat}} \qquad L = W = m_{MTO}\, g \qquad E = \frac{L}{D} \qquad D = \frac{m_{MTO}\, g}{E}$$

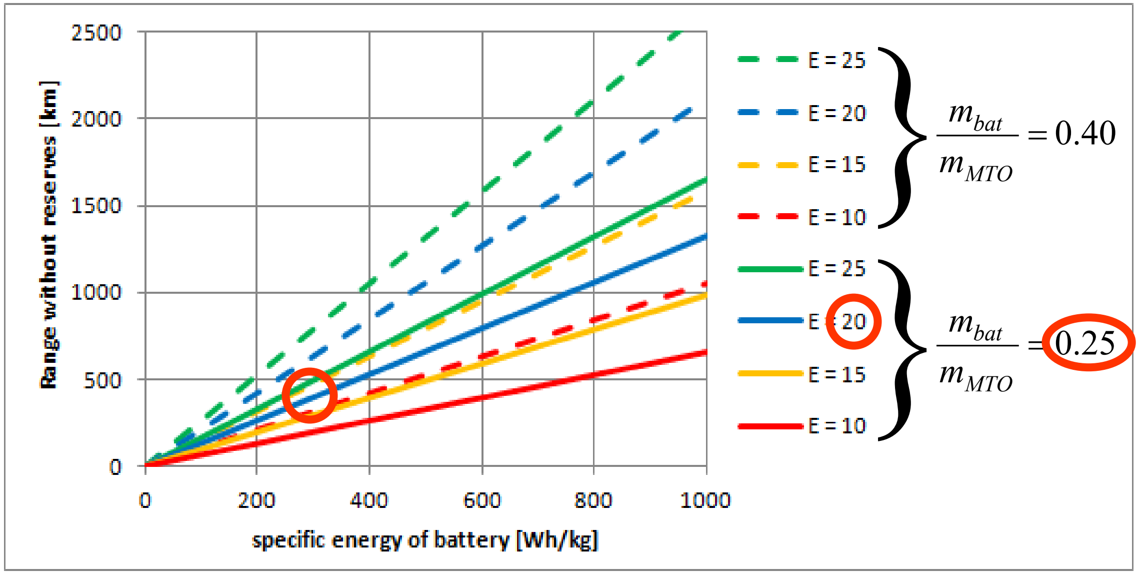
$$P_D = D V = \frac{m_{MTO}\, g}{E} V = P_T = P_{bat}\, \eta_{prop}\, \eta_{elec} \qquad V = \frac{R}{t}$$

$$P_{bat} = \frac{E_{bat}}{t} = m_{bat}\, e_{bat} \frac{V}{R}$$

$$m_{bat}\, e_{bat} \frac{V}{R} \eta_{elec}\, \eta_{prop} = \frac{m_{MTO}\, g}{E} V$$

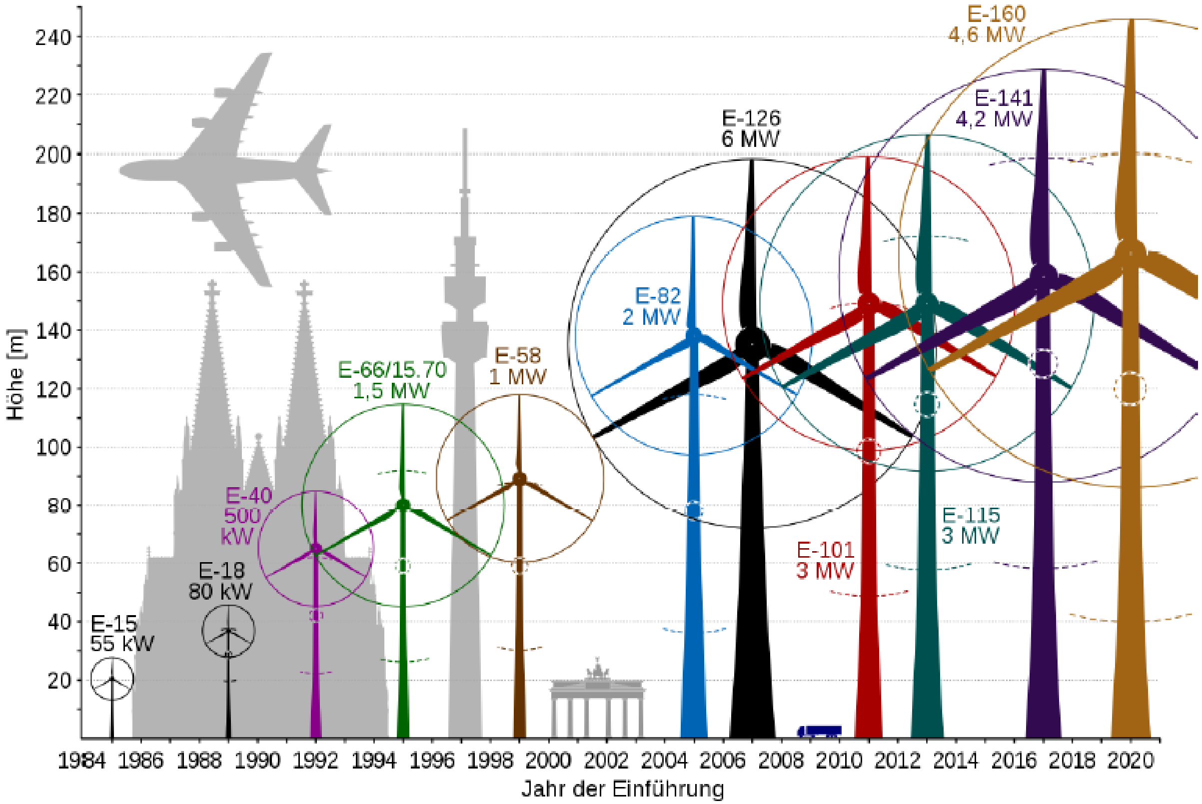
$$\boxed{R = \frac{m_{bat}}{m_{MTO}} \frac{1}{g} e_{bat}\, \eta_{elec}\, \eta_{prop}\, E}$$

$$\eta_{elec} = 0.9; \qquad \eta_{prop} = 0.8$$



○: realistic parameters

Refueling One A350 Once per Day with SAF (E-Fuel): 53 of the Larges Wind Power Plants (4.6 MW each) Are Needed!



| 47 | © Bauhaus Luftfahrt e. V. | 11.11.2020 | Deutsches Museum // RAeS Munich Branch Willy-Messerschmitt-Lecture

Airbus A350-900

Tank Volume: 138 m^3

Fuel Mass:110.4 t (800 kg/m^3)

Energy: 4747.2 GJ (43 MJ/kg)

One E-160 per day: 89.4 GJ SAF

(Capacity Factor: 0.5, η_{PTL} = 0.45)

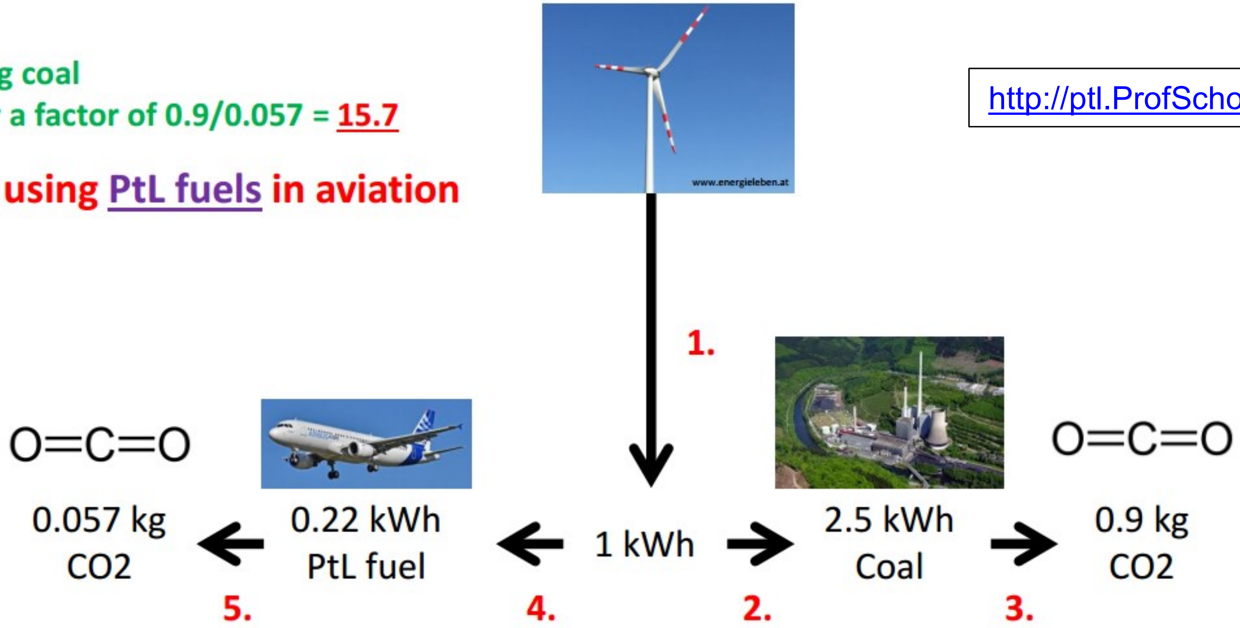
53 E-160 required !

Best: Use Renewable Energy to Replace Coal Power Plants

Substituting coal
is better by a factor of 0.9/0.057 = 15.7

The idea using PtL fuels in aviation

http://ptl.ProfScholz.de



O=C=O 0.057 kg CO2 ← 5. 0.22 kWh PtL fuel ← 4. 1 kWh → 2. 2.5 kWh Coal → 3. 0.9 kg CO2 O=C=O

1.

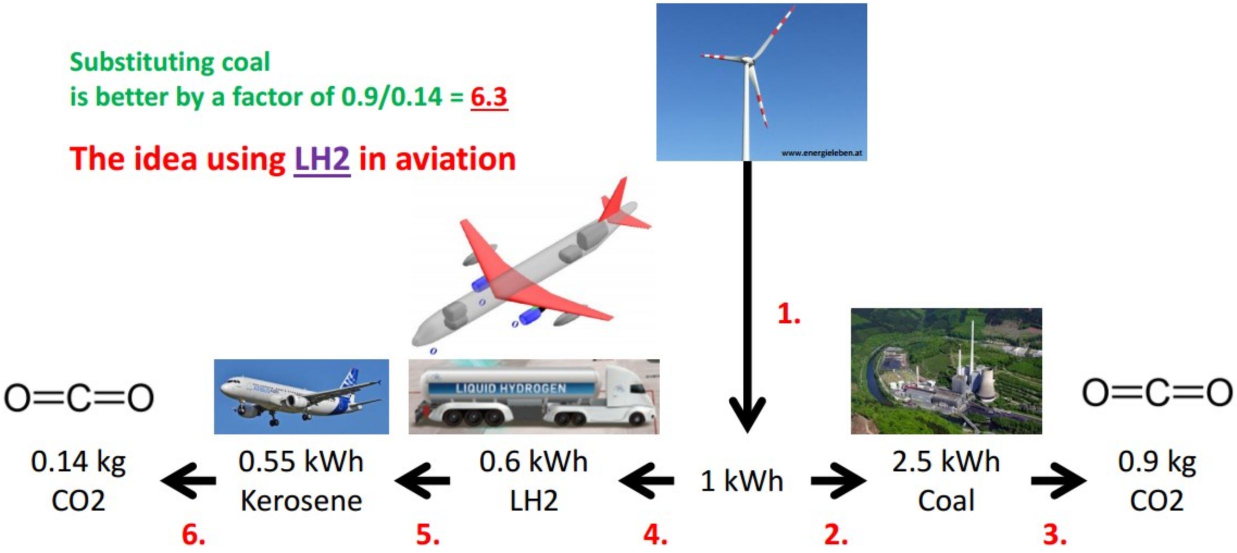
1.) 1 kWh of renewable energy ...
2.) ... can replace 2.5 kWh lignite in coal-fired power plants (efficiency 40%);
3.) This corresponds to 0.9 kg of CO2 (0.36 kg of CO2 for 1 kWh of energy from lignite *).
4.) ... converted into Sustainable Aviation Fuel (SAF) only 0.22 kWh remain (efficiency: 70% electrolysis, 32% Fischer-Tropsch), 99% transport; https://perma.cc/BJJ6-5L74
5.) which save only 0.057 kg of CO2 (0.26 kg of CO2 for 1 kWh of kerosene *).
* UBA, 2016: CO2 Emission Factors for Fossil Fuels. https://bit.ly/3r8avD1

Best: Use Renewable Energy to Replace Coal Power Plants

http://ptl.ProfScholz.de

Substituting coal
is better by a factor of 0.9/0.14 = 6.3

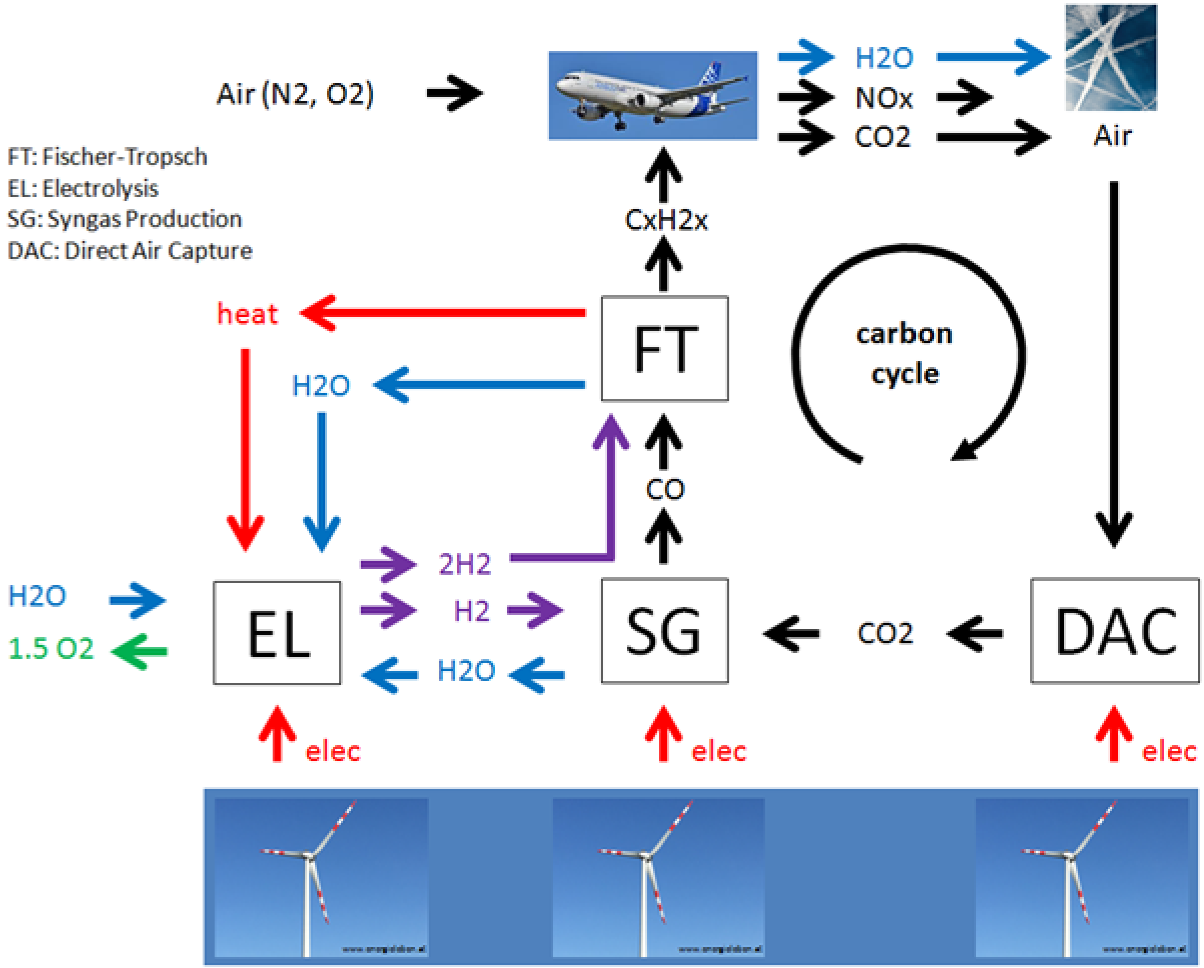
The idea using LH2 in aviation



1.) 1 kWh of renewable energy ...
2.) ... can substitute 2,5 kWh of coal (lignite, brown coal) in a coal power plant (efficiency of a coal power plant: 40%) this is
3.) ... equivalent to 0.9 kg CO2 (0.36 kg CO2 for 1 kWh of energy burning lignite*)
4.) ... but if used in an aircraft it generates LH2 with energy of 0.6 kWh (efficiencies: 70% electrolysis, 83% liquefaction & transport)
5.) LH2 aircraft consume (say) 10% more energy (higher operating empty mass, more wetted area); so a kerosene aircraft needs ...
6.) only 0.55 kWh, which can be substituted. This is equivalent to 0.14 kg CO2 (0.26 kg CO2 for 1 kWh of energy burning kerosene*).
7.) Note: Not considered is that hydrogen aircraft may come with higher non-CO2 effects than kerosene aircraft.

* UBA, 2016. CO2 Emission Factors for Fossil Fuels. Available from: https://bit.ly/3r8avD1

The Carbon Cycle of Sustainable Aviation Fuel (SAF, E-Fuel)



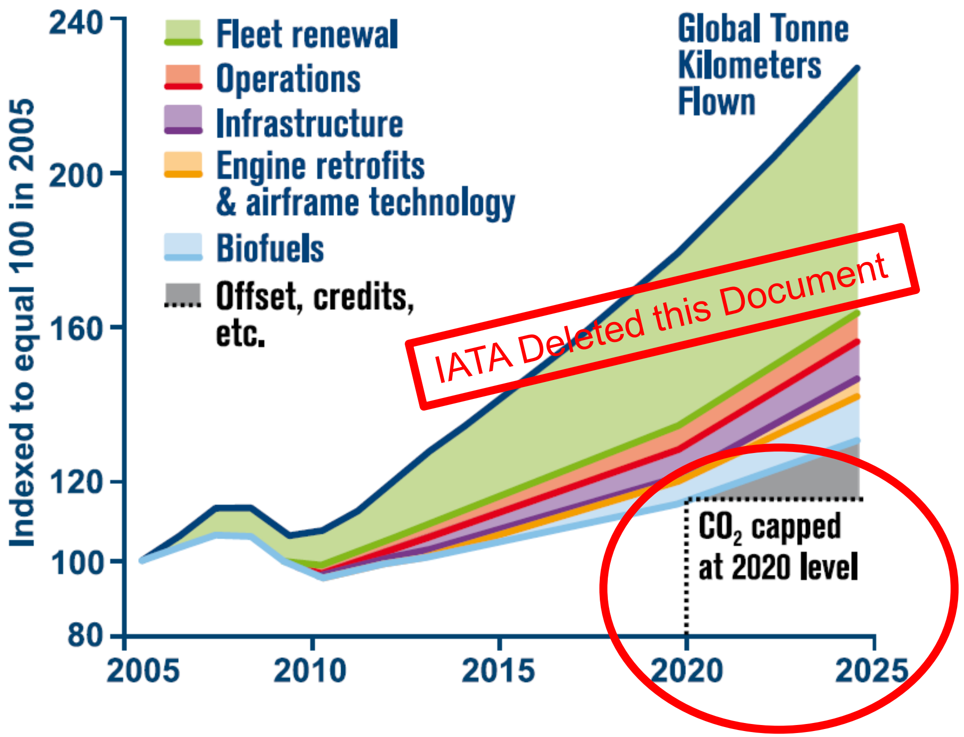
- **SAF need DAC** **(Direct Air Capure) to compensate for CO2 ("cabon cycle")**
- **In addition: SAF and BioFuel need more DAC to compensate for the global warming effect due to**
    - **NOX and**
    - **H2O (AIC)**

Production of synthetic kerosene (e-fuel) with power-to-liquid (PtL). Taking CO2 from the air (Direct Air Capture, DAC) enables a carbon cycle.

Goal Setting

International Air Transport Association (IATA) in 2009:

Carbon-Neutral Growth (CNG) from 2020



2020 is arbitrary year to start with CO2 compensation.

Compensation could have started earlier.

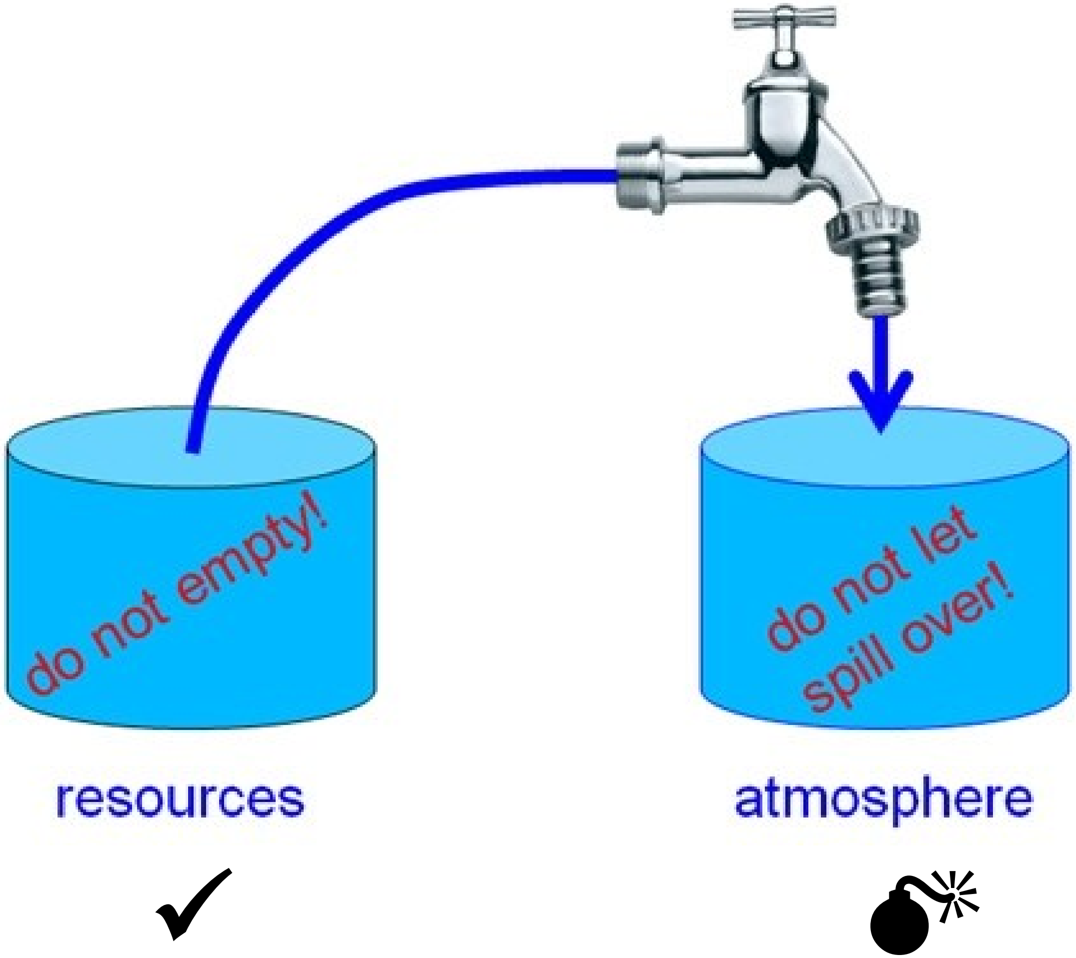
Why not postpone longer?

Did we notice any change in 2020 with this CO2 cap?

IATA (and ATAG) wanted to achieve zero emission growth from 2020 onwards. This is only possible with CO2 compensation (carbon offset schemes). 2020: Corona pandemic!

Archived at: https://perma.cc/42HW-ZTKF

Fuel Consumption (Resources) or Emissions (Atmosphere)?



With Carbon Neutral Growth (CNG) the tap is left wide open.

Maybe it is time to close the tap a least a little?

Yes, with "zero emission"!

Airbus, 2020: "Zero-Emission" Hybrid-Hydrogen Passenger Aircraft

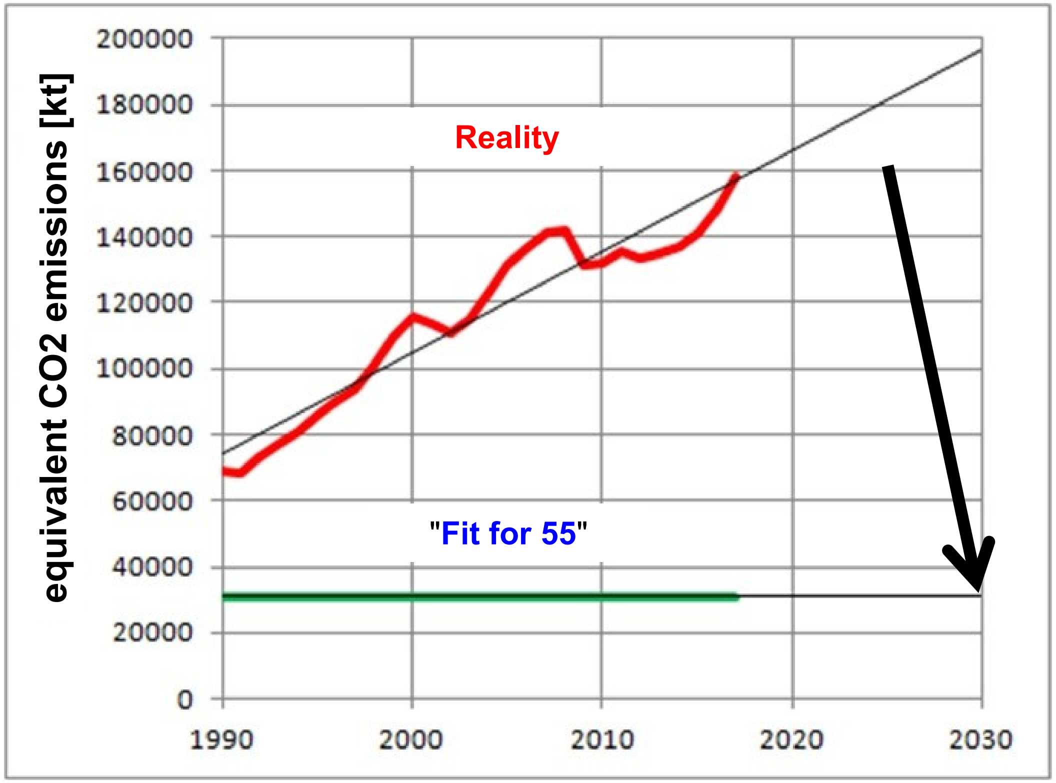
https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html
Archived at: https://perma.cc/HJ6L-3HUB

"At Airbus, we have the ambition to develop the world's first zero-emission commercial aircraft by 2035."
(2020-09-21)

Airbus, 2023/2024: No Hydrogen Flight Demonstrator Launched

Introducing #ZEROe, 2020-09-21, https://youtu.be/525YtyRi_Vc. Left to right: Jean-Brice Dumont (Executive Vice President Engineering, Airbus), Glenn Llewelyn (Vice President Head of Zero Emission Aircraft, Airbus), Grazia Vittadini (Chief Technology Officer, Airbus).

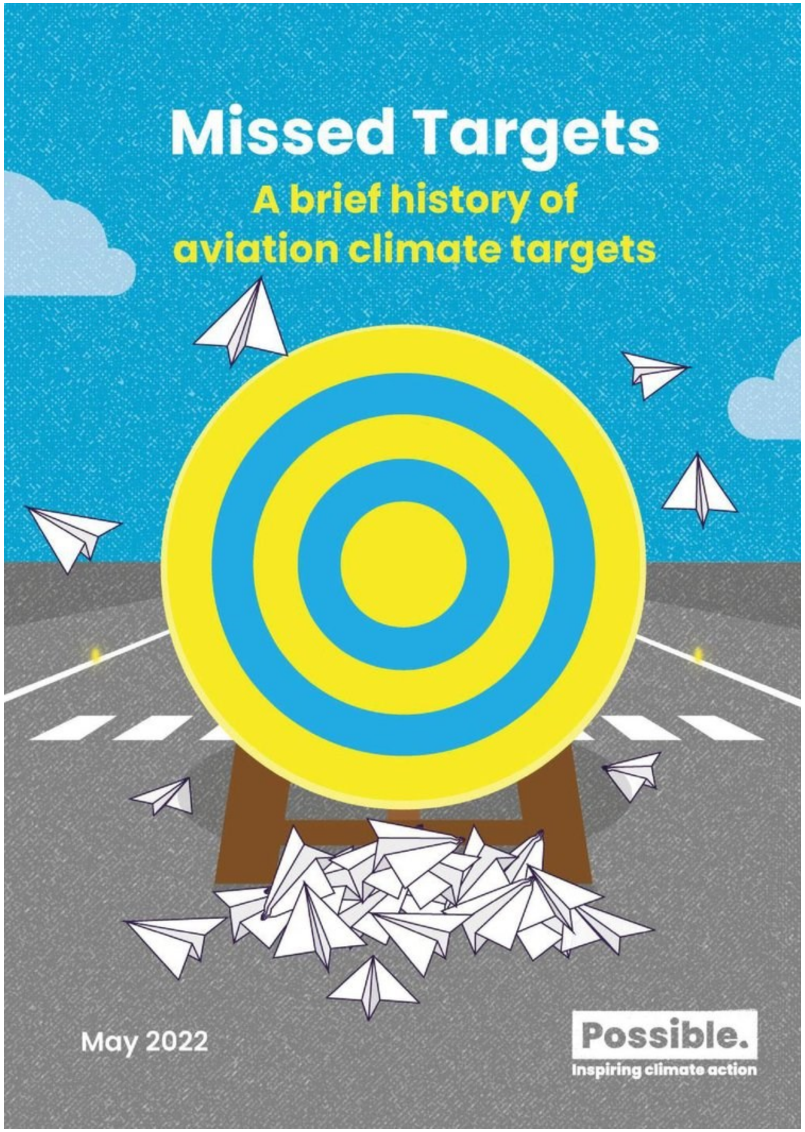
What are the EU's Climate Targets?



1.) 2019: The EU's "**Green Deal**": "In 2050, net greenhouse gas emissions should no longer be released".

2.) 2020: The European climate targets for 2030 were defined under the motto "**Fit for 55**". This is the interim goal of the Green Deal: Greenhouse gas emissions are to be reduced by 55% compared to 1990 – i.e. only 45% of the 1990 value. This value is to be achieved by 2030.

The 55% reduction compared to 1990 means a reduction of more than 80% for aviation by 2030, i.e. by about 9% per year. Fuel consumption has so far been reduced by 1.5% annually through operational measures and technology. **Air traffic would therefore have to shrink permanently by 12% per year (regardless of the short-term impact of the pandemic)** based on 2024 traffic numbers.



"This report assessed every public climate target which the international aviation industry set itself since 2000.

We found that all but one of over 50 separate climate targets has either been missed, abandoned or simply forgotten about.

Overall, the industry's attempts to regulate its emissions and set its own targets suffered from a combination of unclear definitions, shifting goalposts, inconsistent reporting, a complete lack of public accountability and, in some cases, [goals] being quietly dropped altogether."

URL: https://www.wearepossible.org/our-reports-1/missed-target-a-brief-history-of-aviation-climate-targets

Archived: https://perma.cc/4SYC-UL93

European Commission - Press release

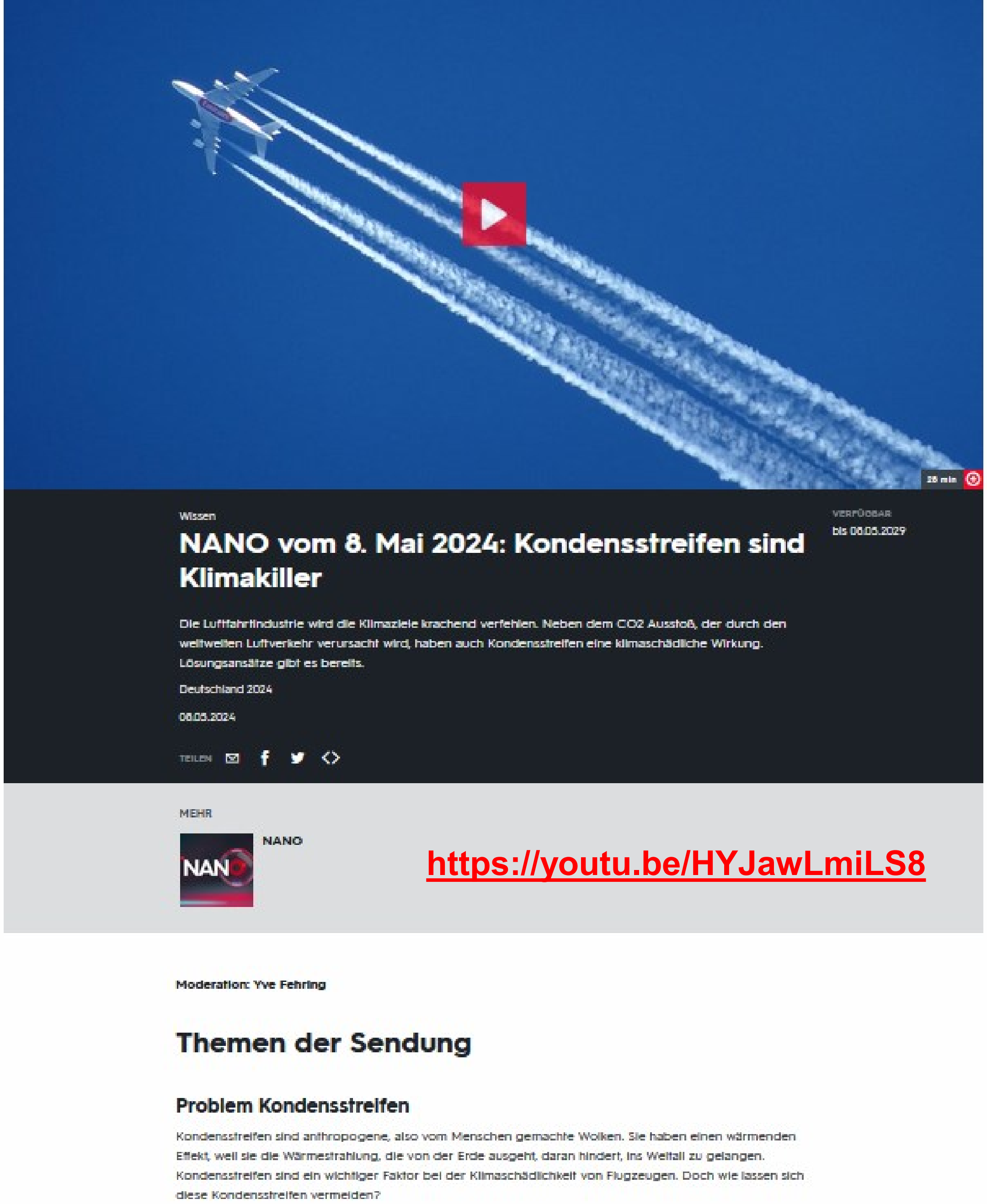
Commission and national consumer protection authorities starts action against 20 airlines for misleading greenwashing practices

Brussels, 30 April 2024

Following an alert from the European Consumer Organisation (BEUC), the European Commission and EU consumer authorities (Network of Consumer Protection Cooperation - CPC - Authorities) sent letters to 20 airlines identifying several types of potentially misleading green claims and inviting them to bring their practices in line with EU consumer law within 30 days.

Archived at: https://perma.cc/VJC3-AQDX

Contrails



Wissen

NANO vom 8. Mai 2024: Kondensstreifen sind Klimakiller

VERFÜGBAR
bis 08.05.2029

Die Luftfahrtindustrie wird die Klimaziele krachend verfehlen. Neben dem CO2 Ausstoß, der durch den weltweiten Luftverkehr verursacht wird, haben auch Kondensstreifen eine klimaschädliche Wirkung. Lösungsansätze gibt es bereits.

Deutschland 2024

08.05.2024

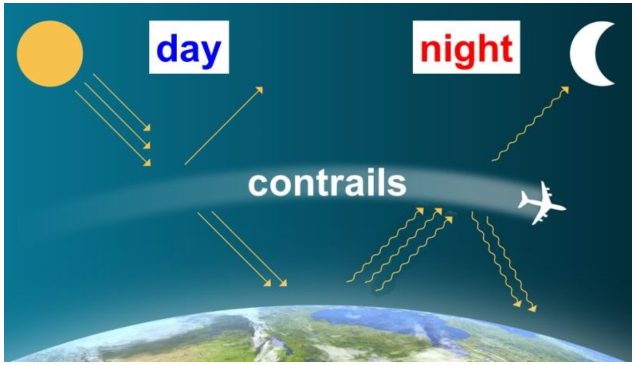
https://youtu.be/HYJawLmiLS8

Moderation: Yve Fehring

Themen der Sendung

Problem Kondensstreifen

Kondensstreifen sind anthropogene, also vom Menschen gemachte Wolken. Sie haben einen wärmenden Effekt, weil sie die Wärmestrahlung, die von der Erde ausgeht, daran hindert, ins Weltall zu gelangen. Kondensstreifen sind ein wichtiger Faktor bei der Klimaschädlichkeit von Flugzeugen. Doch wie lassen sich diese Kondensstreifen vermeiden?



Contrails:
Basics

Contrail Life Cycle

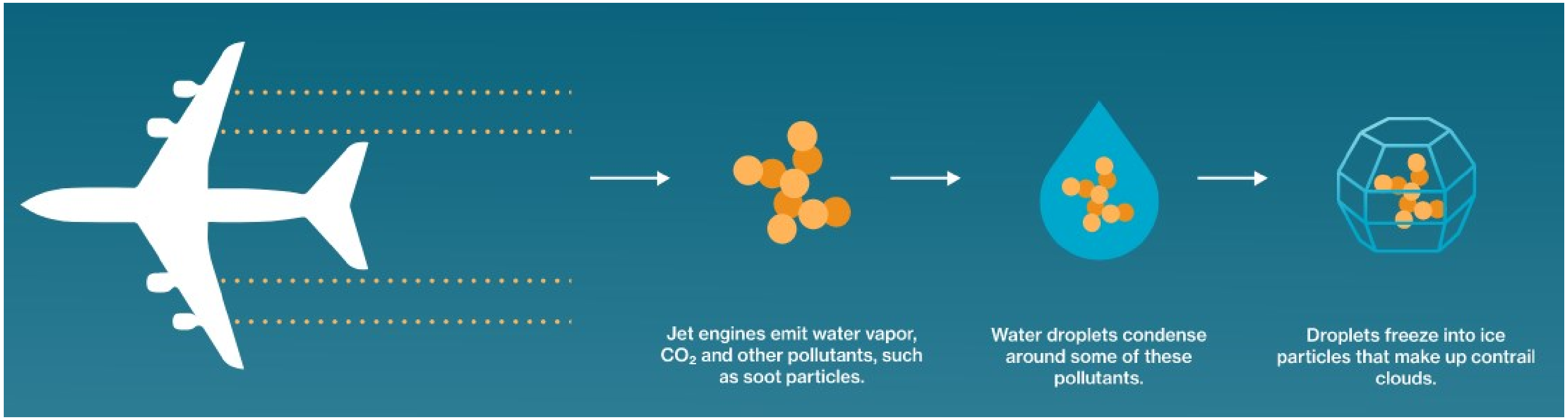
KRAFT, Martin, 2016. Kondensstreifen, CC BY-SA, https://de.wikipedia.org/wiki/Kondensstreifen#/media/Datei:MK35097_Contrails.jpg

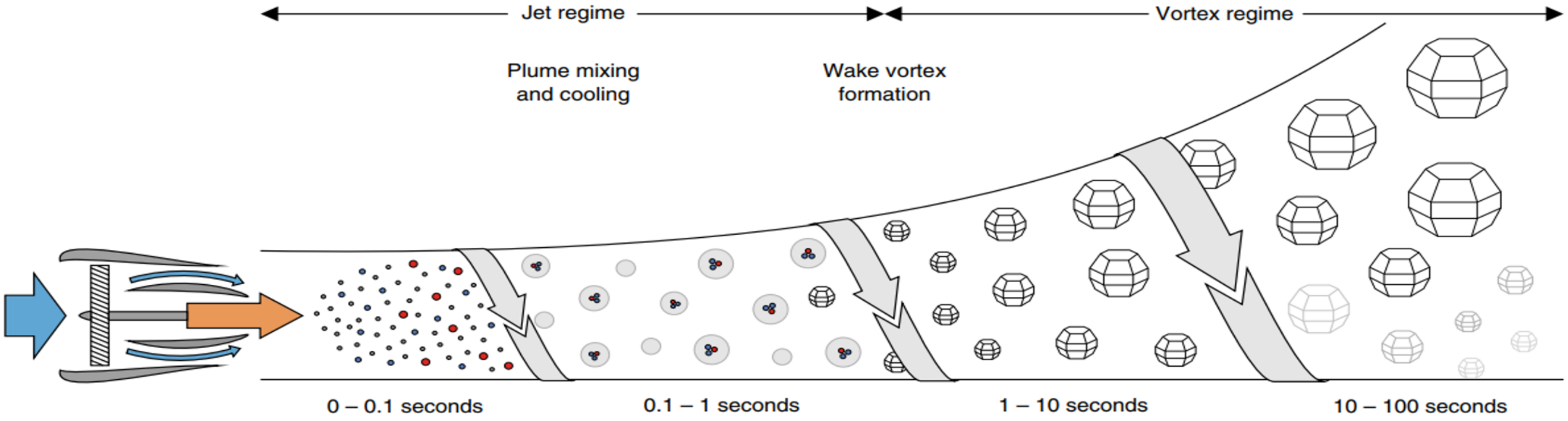
Cooling Persistent Contrails (Daytime)

Warming Persistent Contrails (Night, Dawn, Dusk)

Ice Crystal Growth in Contrails

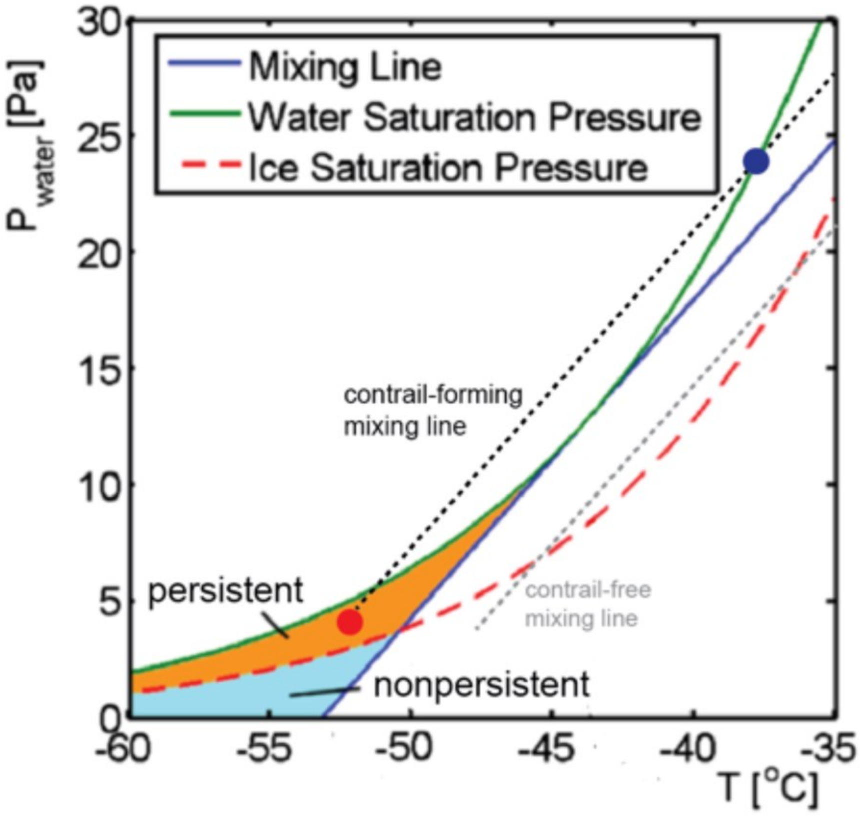
https://contrails.org/science





KÄRCHER, Bernd, 2018. Formation and Radiative Forcing of Contrail Cirrus. In: *Nature Communications*, Vol. 9, Article Number: 1824. Available from: https://doi.org/10.1038/s41467-018-04068-0

Exhaust Gas Mixing in Ambient Air



Graphical representation of the Schmidt-Appleman criterion analysis. When the mixing line (representing mixing of engine exhaust and ambient air) crosses the water saturation line, a contrail will form. As the mixture continues to cool and water deposits as ice, the mixing may cease in ice supersaturated conditions (shaded orange) where a contrail will persist.

NOPPEL, F., SINGH, R., 2007. Overview on Contrail and Cirrus Cloud Avoidance Technology. In: Journal of Aircraft, vol. 44, no. 5. Available from: https://doi.org/10.2514/1.28655
via
BREAKTHROUGH ENERGY, 2023. Contrails & Climate Change. Archived at: https://perma.cc/YT8Q-V3KW

Schmidt-Appleman Criterion for Contrail Formation

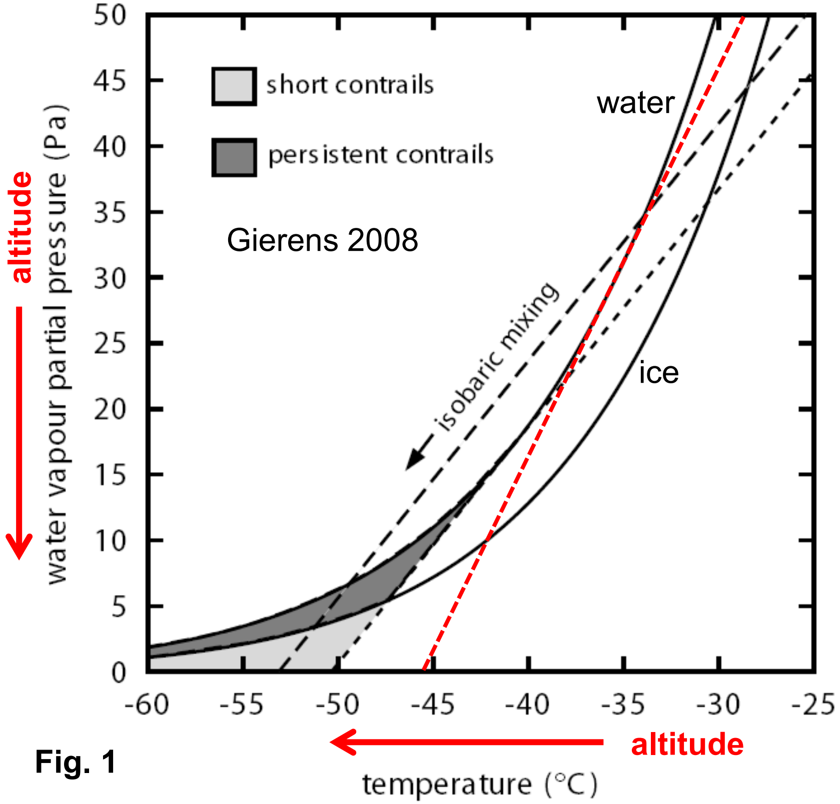


Fig. 1

The mixing process is assumed to take place isobarically, so that on a T-e diagram the mixing (phase) trajectory appears as a straight line (e is the partial pressure of water vapour in the mixture, T is its absolute temperature, see Fig. (**1**)). The slope of the phase trajectory, G (units Pa/K), is characteristic for the respective atmospheric situation and aircraft/engine/fuel combination. G is given by

$$G = \frac{EI_{H2O} p c_p}{\varepsilon Q(1-\eta)}$$

where ε is the ratio of molar masses of water and dry air (0.622), c_p=1004 J/(kg K) is the isobaric heat capacity of air, and p is ambient air pressure. G depends on fuel characteristics (emission index of water vapour, EI_{H2O} = 1.25 kg per kg kerosene burnt; chemical heat content of the fuel, Q = 43 MJ per kg of kerosene), and on the overall propulsion efficiency η of aircraft. Modern airliners have a propulsion efficiency (η) of approximately 0.35.

G is the slope of the dotted line.

The dotted line is tangent to the water saturation line.

A steep dotted line (large G) means:

Contrails more often and also at lower altitudes.

GIERENS, Klaus, LIM, Limg, ELEFTHERATOS, Kostas, 2008. A Review of Various Strategies for Contrail Avoidance.
In: The Open Atmospheric Science Journal, 2008, 2, 1-7. Available from: https://doi.org/10.2174/1874282300802010001

Heating Value Q, Emission Index EI, and Slope G

fuel	Q [MJ/kg]	EI_{H2O} [kg/kg]	EI_{H2O}/Q [kg/MJ]	$G_{H2}/G_{Jet\text{-}A1}$
H2	120	8,94	0,0745	2,58
Jet –A1	43	1,24	0,0288	

The slope G of the dotted line is 2,58 times steeper in case of LH2 combustion.This means: Contrails more often and also at lower altitudes.

2,58 times more water vapor is produced with LH2 combustion compared to kerosene combustion (for the same energy used).

Calculating Saturation Pressure with the Magnus Equation

The saturation vapor pressure for water vapor in the pure phase (absence of air) can be calculated using the Magnus formula recommended by the WMO. This formula has the advantage that it requires only three parameters and is reversible. However, more accurate formulas exist. The ones shown here have an accuracy (standard deviation) of ±0.3% over water and ±0.5% over ice.

Over flat water surfaces

$$E_w(t) = 6{,}112\,\mathrm{hPa} \cdot \exp\left(\frac{17{,}62 \cdot t}{243{,}12\,^\circ\mathrm{C} + t}\right) \qquad \text{für} \quad -45\,^\circ\mathrm{C} \leq t \leq 60\,^\circ\mathrm{C}$$

Over flat ice surfaces

$$E_i(t) = 6{,}112\,\mathrm{hPa} \cdot \exp\left(\frac{22{,}46 \cdot t}{272{,}62\,^\circ\mathrm{C} + t}\right) \qquad \text{für} \quad -65\,^\circ\mathrm{C} \leq t \leq 0\,^\circ\mathrm{C}$$

WMO, 2018. Measurement of Meteorological Variables. In: Guide to Instruments and Methods of Observation, Annex 4.B Formulae for the Computation of Measures of Humidity. Archived at:
https://web.archive.org/web/20220205104246/https://library.wmo.int/doc_num.php?explnum_id=10616
via
https://de.wikipedia.org/wiki/Sättigungsdampfdruck

The Tangent Mixing Line of the Schmidt-Appleman Criterion

Determination of the straight line in the Schmidt-Appleman criterion. We only know the slope, G of the straight line

$$f(t) = G\,t + G_0$$

$f(t)$ is the tangent to $E_w(t)$. At the point of contact, the slope of $E_w(t)$ and $f(t)$ must be the same. $E_w(t)$ is differentiated with respect to t and set equal to G.

$$E_w(t)' = \frac{dE_W(t)}{dt} = G$$

This gives the temperature t_{SAC} at the point of contact. The temperature t_{SAC} is the highest temperature at which a contrails can form. Furthermore, $E_w(t) = f(t)$ at point of contact. From this we obtain G_0 .

$$G_0 = E_w(t) - G\,t$$

The Tangent Mixing Line of the Schmidt-Appleman Criterion

$$E_w(t) = a \cdot e^{\frac{bt}{c+t}}$$

$$\frac{dE_w(t)}{dt} = a \cdot e^{\frac{bt}{c+t}} \cdot \frac{b(c+t) - bt}{(c+t)^2}$$

$$= a \cdot e^{\frac{bt}{c+t}} \cdot \frac{bc + bt - bt}{(c+t)^2}$$

$$\frac{dE_w(t)}{dt} = \frac{abc \cdot e^{\frac{bt}{c+t}}}{(c+t)^2}$$

$$\overset{!}{=} \quad G$$

$$f(t) = G \cdot t + G_0$$

Magnus formula for saturation water vapor pressure over a flat water surface

a = 6.112 hPa

b = 17.62

c = 243.12 °C

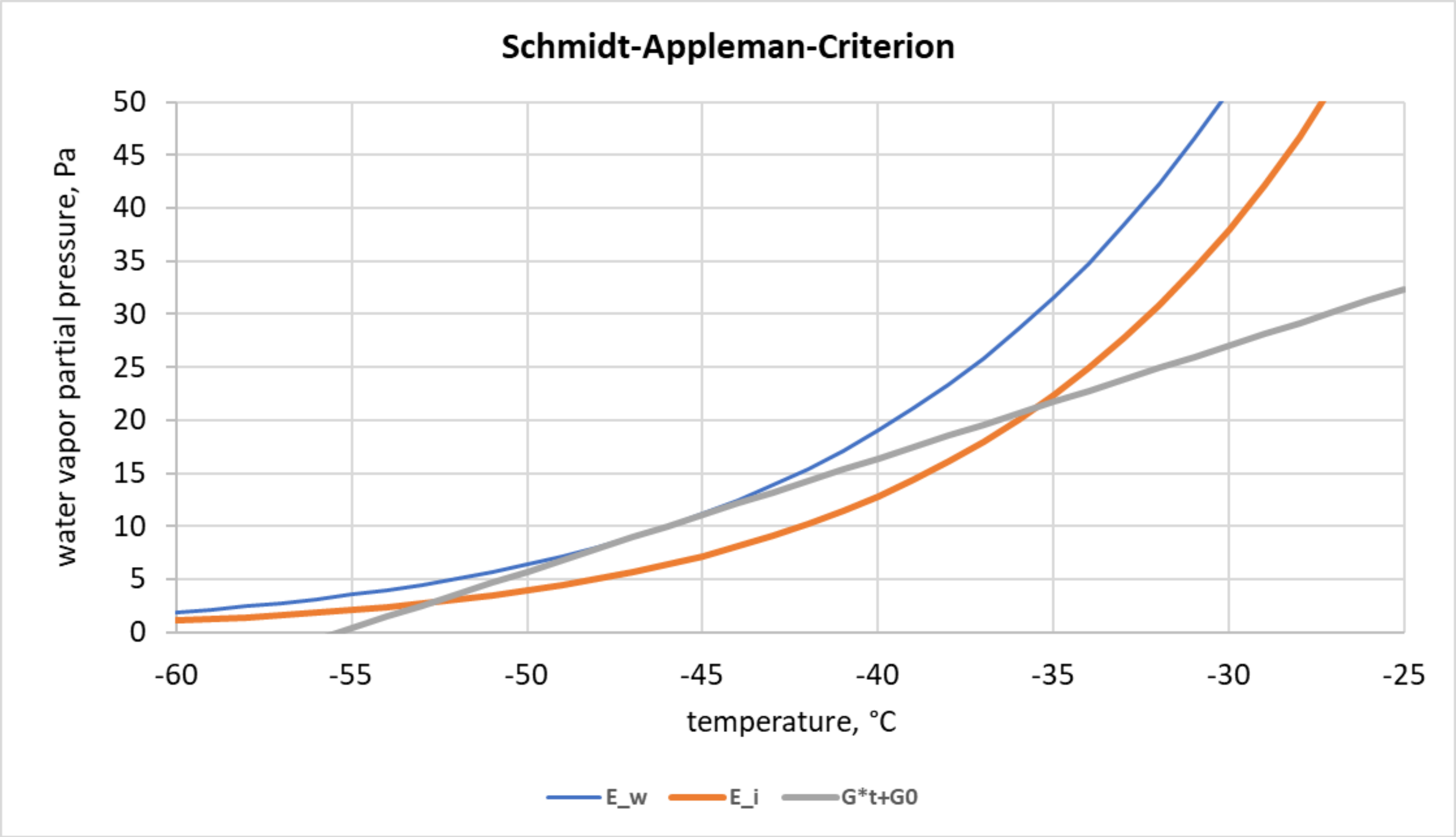
This equation can be solved for *t* with the SOLVER in Excel

$$\frac{abc \cdot e^{\frac{bt}{c+t}}}{(c+t)^2} - G = 0$$

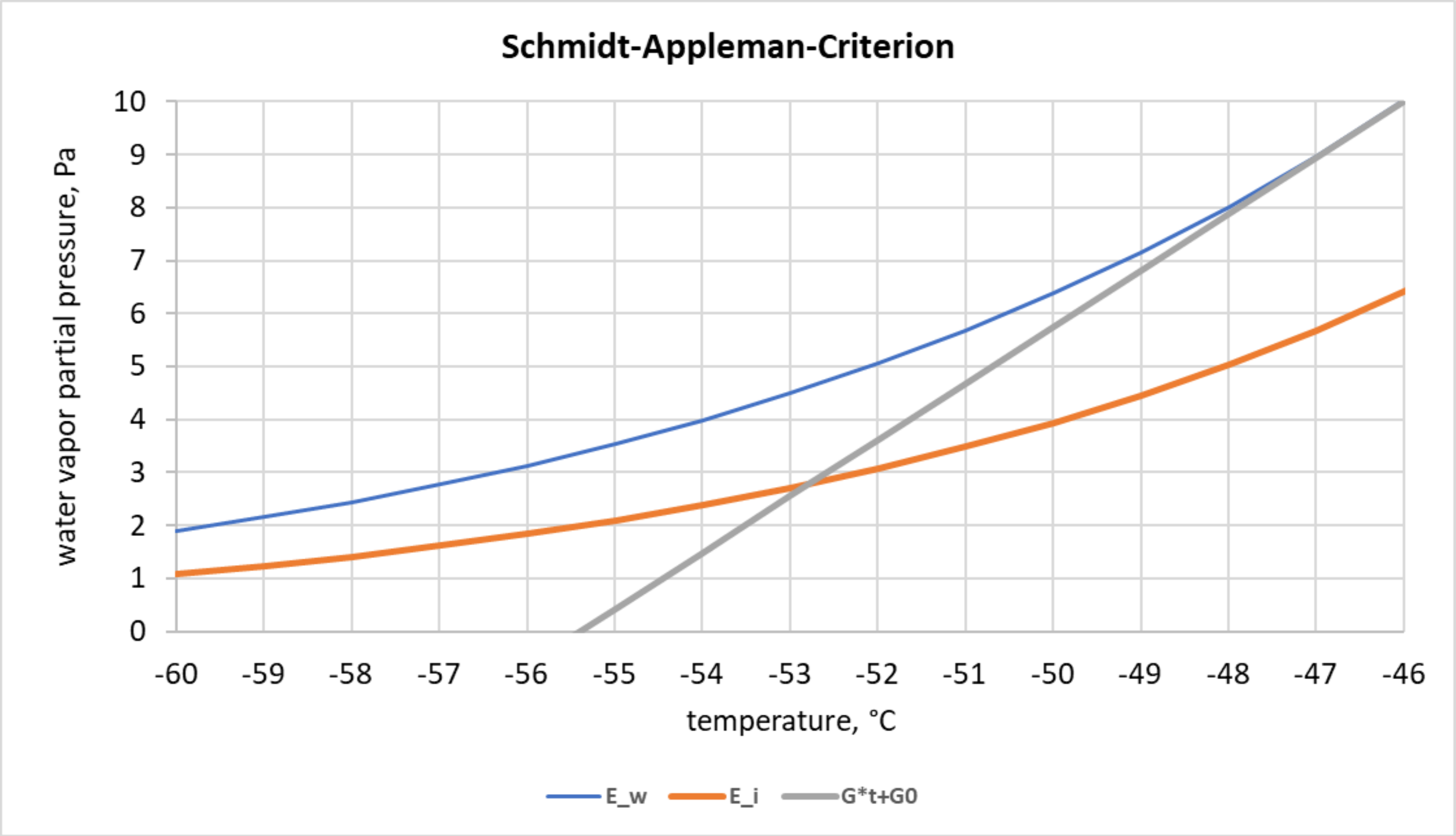
The temperature, *t* is where $E_w(t)$ and f(t) touch. This temperature is call t_{SAC}.
It is the highest temperature for contrails to form.

SAC stands for Schmidt-Appleman Criterion.

Schmidt-Appleman Criterion (Scholz)



Schmidt-Appleman Criterion, Zoom In (Scholz)



Constructing the Schmidt-Appleman Diagram

An aircraft flies at altitude, *H* and air temperature, *t*.
At what relative humidity, φ does it show contrails?

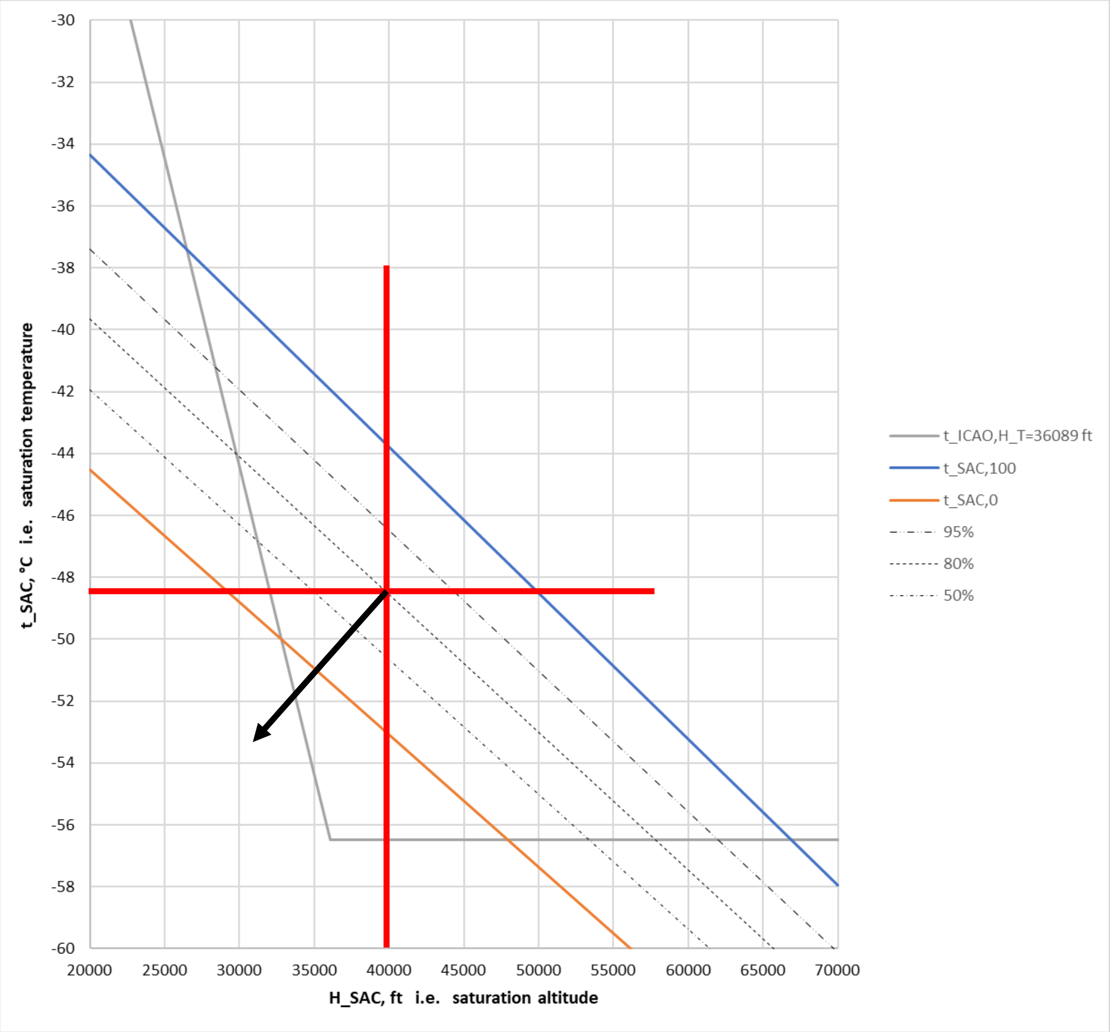
$$G \cdot t + G_0 = \rho \cdot E_W(t)$$

$$\boxed{\rho = \frac{G \cdot t + G_0}{E_W(t)}}$$

Exact solution of this equation with Excel's Solver.

Results need to be limited, if:
$G\ t + G_0 < 0$ => φ < 0% (not defined)
$t > t_{SAC}$ => φ > 100% (not defined)

Schmidt-Appleman Diagram (Scholz)



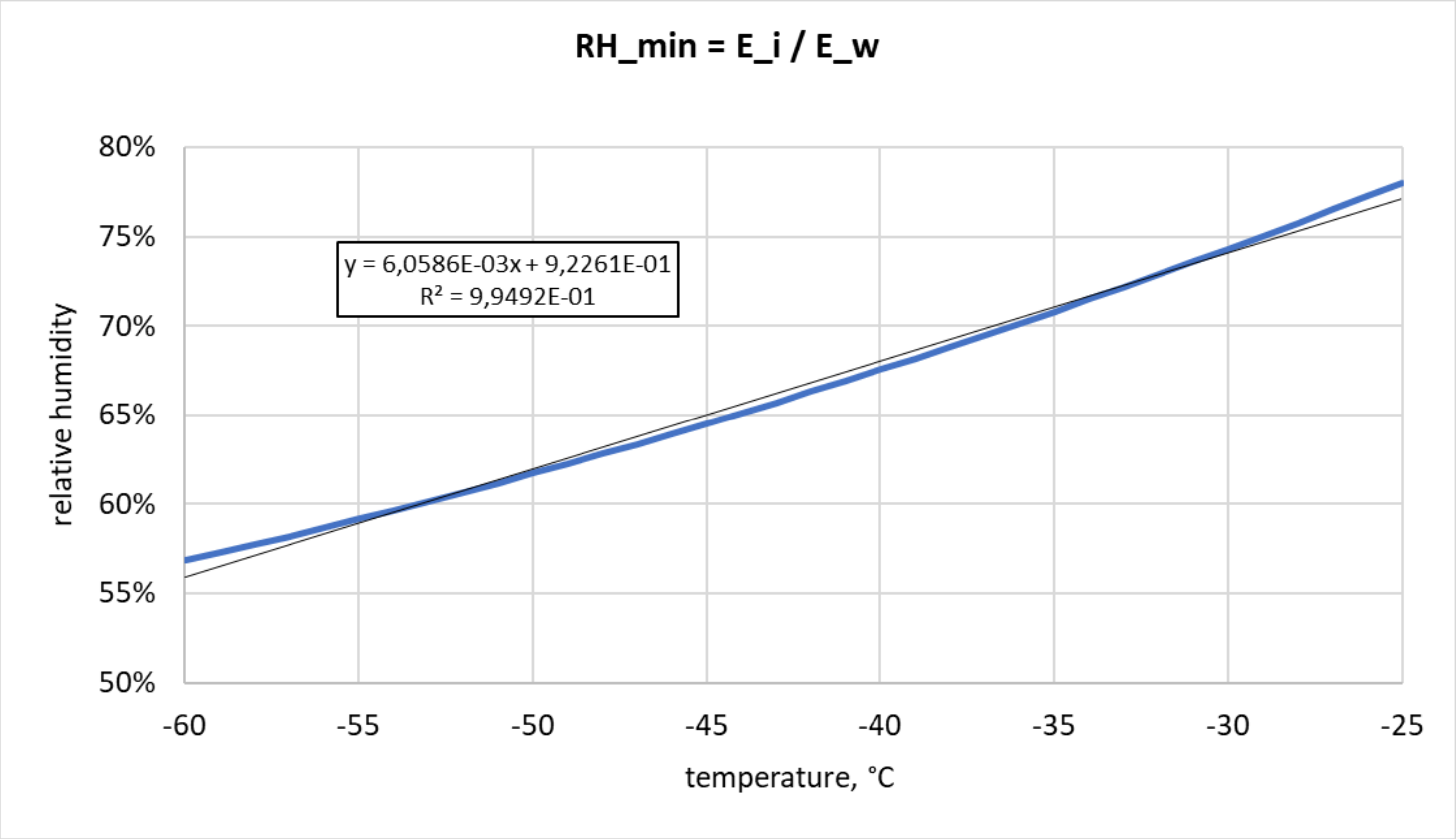
An aircraft flies at altitude, *H* and air temperature, *t*.

The red cross shows: There is one relative humidity, φ at which the aircraft starts to show contrails!

If the relative humidity is less than φ, it must be colder, or the same low temperature must occur at lower altitudes.

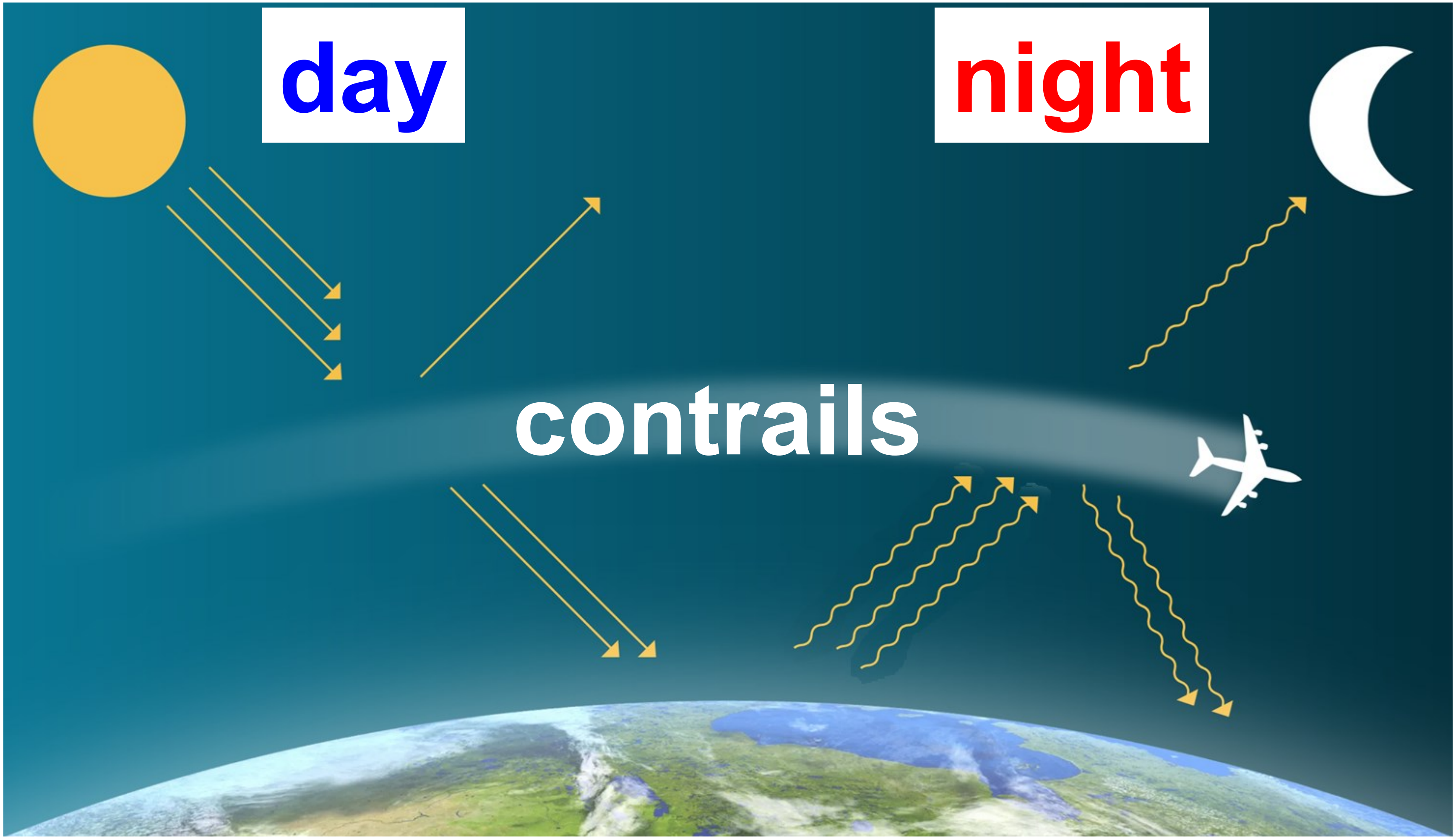
Contrails form down or left of the respective humidity lines. See black arrow.

Minimum Relative Humidity for Persistent Contrails

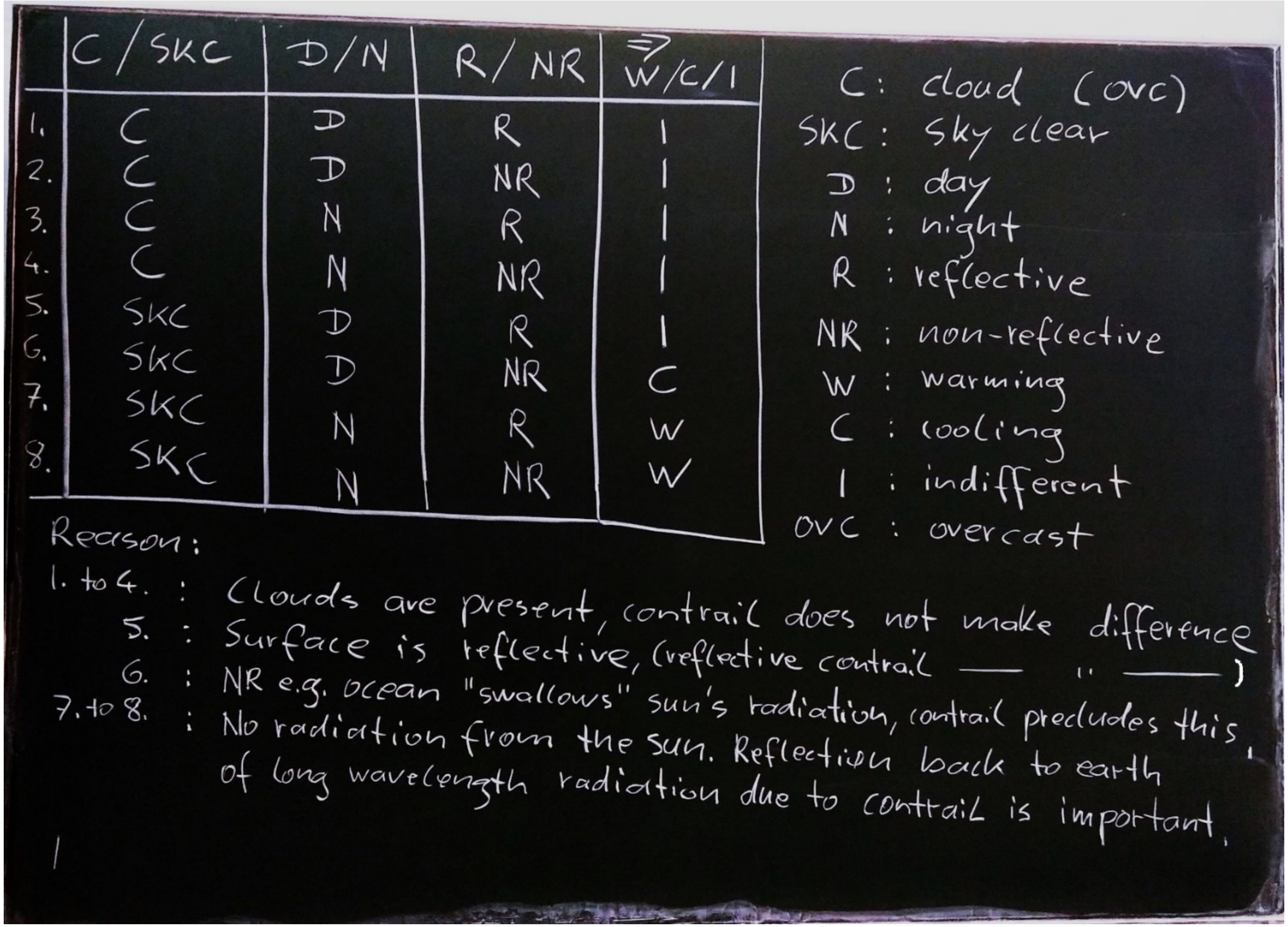


Ice crystals tend to sublimate (go directly from the solid to the gas phase) or dry up, if the air is dry enough. The blue line shows the relative humidity, above which ice does not sumblimate anymore and contrails are persistent.

Cooling (Day) versus Warming (Night) Contrails



Systematic of Cooling and Warming Contrails



	C / SKC	D / N	R / NR	⇒ W / C / I
1.	C	D	R	I
2.	C	D	NR	I
3.	C	N	R	I
4.	C	N	NR	I
5.	SKC	D	R	I
6.	SKC	D	NR	C
7.	SKC	N	R	W
8.	SKC	N	NR	W

C : cloud (ovc)
SKC : sky clear
D : day
N : night
R : reflective
NR : non-reflective
W : warming
C : cooling
I : indifferent
OVC : overcast

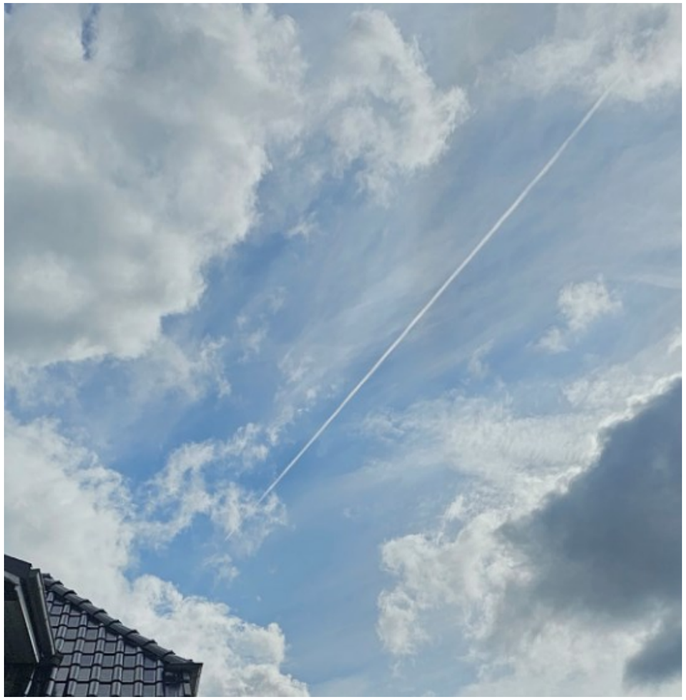
Reason:

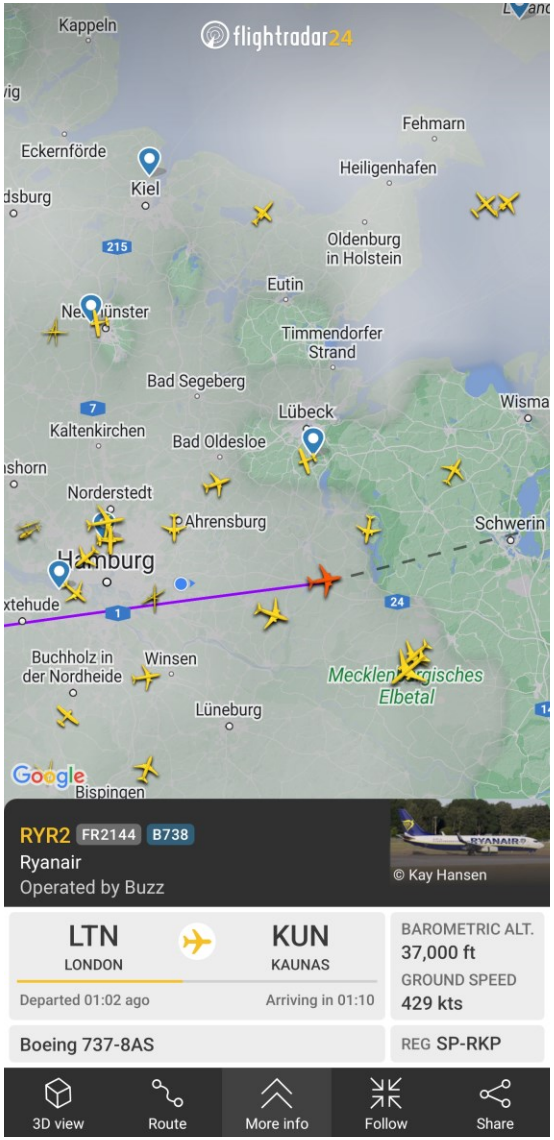
1. to 4. : Clouds are present, contrail does not make difference
5. : Surface is reflective, (reflective contrail —— " ——)
6. : NR e.g. ocean "swallows" sun's radiation, contrail precludes this.
7. to 8. : No radiation from the sun. Reflection back to earth of long wavelength radiation due to contrail is important.

Observation & Prediction

Observation & Prediction

At 10:53 AM, on September 3, a Boeing 737-8AS, registration SP-RKP, was flying eastbound. This plane left a persistent contrail. The aircraft was at a GPS altitude of 38800 ft (FL 370). The outside temperature was -53 °C.



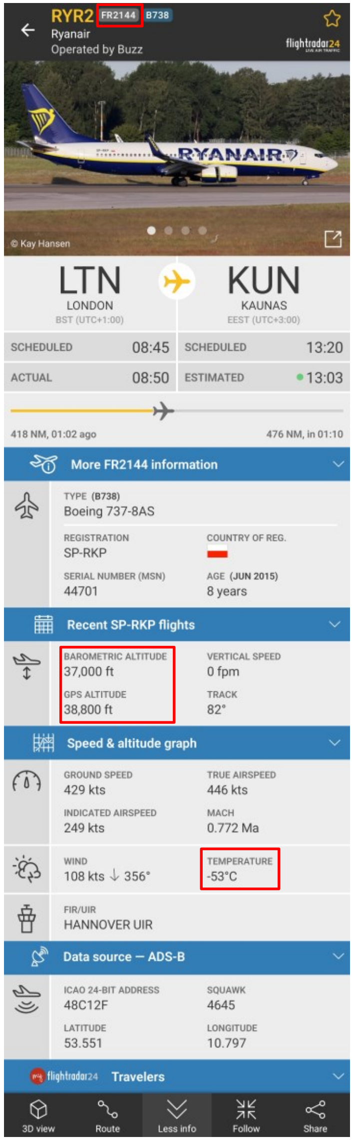


RYR2 FR2144 B738
Ryanair
Operated by Buzz
© Kay Hansen

LTN LONDON → KUN KAUNAS
Departed 01:02 ago
Arriving in 01:10

BAROMETRIC ALT. 37,000 ft
GROUND SPEED 429 kts

Boeing 737-8AS
REG SP-RKP



RYR2 FR2144 B738
Ryanair
Operated by Buzz
flightradar24 LIVE AIR TRAFFIC
© Kay Hansen

LTN LONDON BST (UTC+1:00)
KUN KAUNAS EEST (UTC+3:00)

SCHEDULED	08:45	SCHEDULED	13:20
ACTUAL	08:50	ESTIMATED	13:03

418 NM, 01:02 ago
476 NM, in 01:10

More FR2144 information

TYPE (B738): Boeing 737-8AS
REGISTRATION: SP-RKP
COUNTRY OF REG.: 🟥
SERIAL NUMBER (MSN): 44701
AGE (JUN 2015): 8 years

Recent SP-RKP flights

BAROMETRIC ALTITUDE: 37,000 ft
VERTICAL SPEED: 0 fpm
GPS ALTITUDE: 38,800 ft
TRACK: 82°

Speed & altitude graph

GROUND SPEED: 429 kts
TRUE AIRSPEED: 446 kts
INDICATED AIRSPEED: 249 kts
MACH: 0.772 Ma
WIND: 108 kts ↓ 356°
TEMPERATURE: -53°C
FIR/UIR: HANNOVER UIR

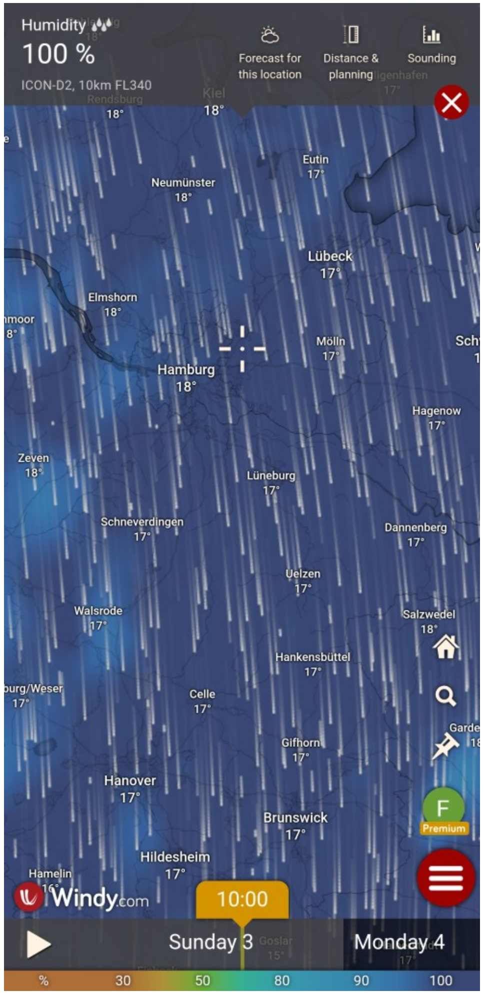
Data source — ADS-B

ICAO 24-BIT ADDRESS: 48C12F
SQUAWK: 4645
LATITUDE: 53.551
LONGITUDE: 10.797

flightradar24 Travelers

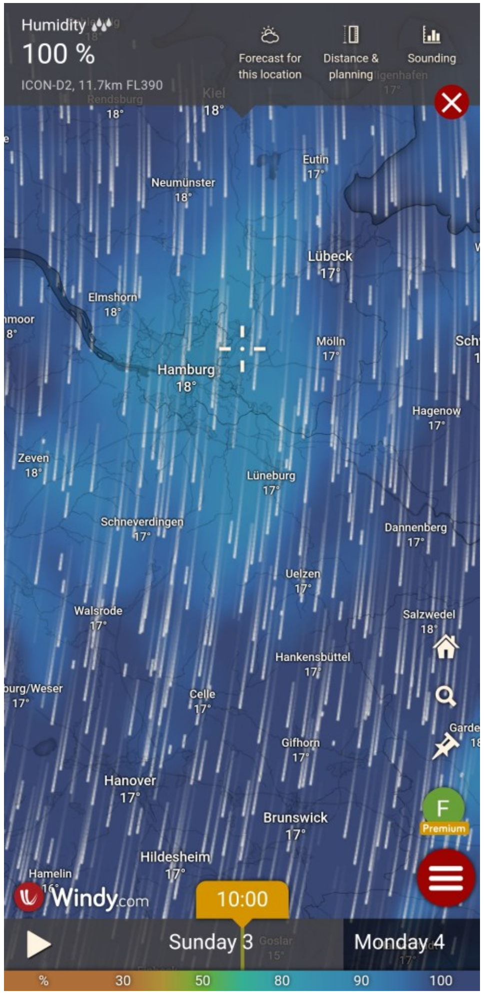
EGGW
-
EYKA

Relative Humidity



Humidity 100 %

ICON-D2, 10km FL340



Humidity 100 %

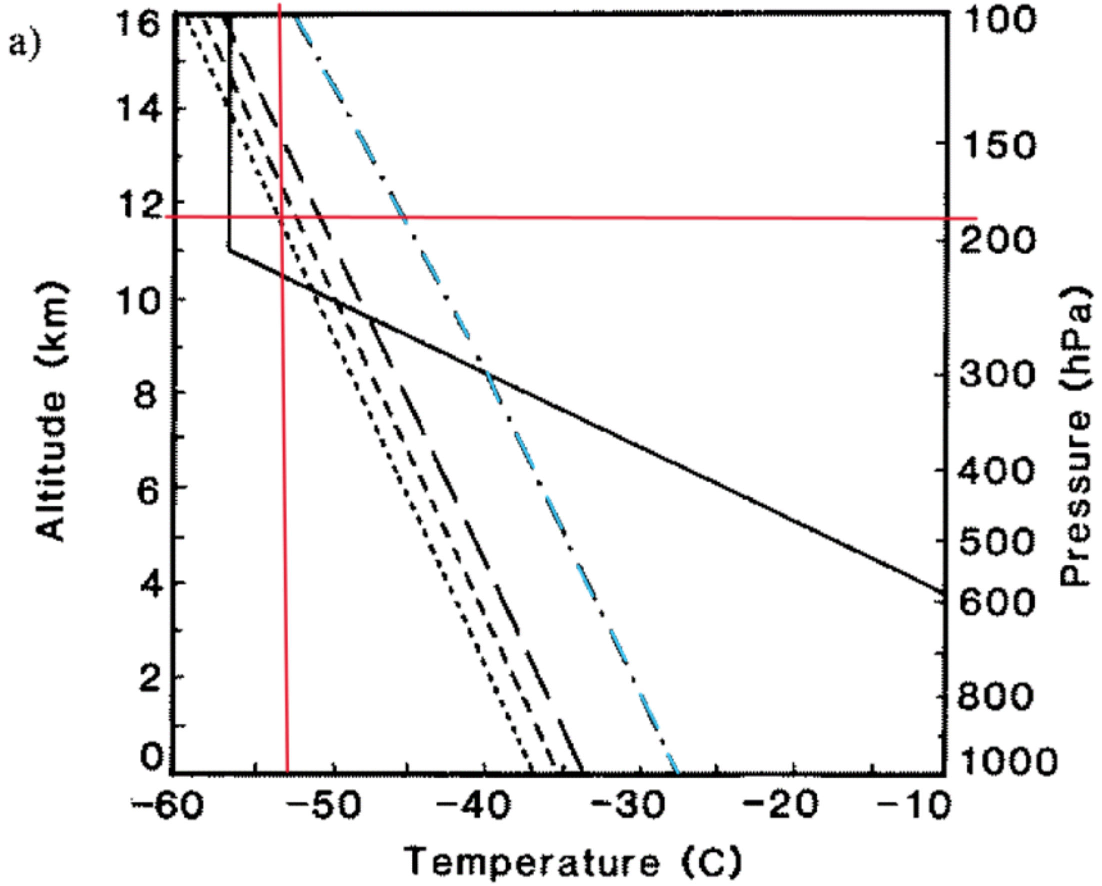
ICON-D2, 11.7km FL390

Relative humidity at FL340: 100%

Relative humidity at FL390: 100%

Interpolated relative humidity at FL370: 100%

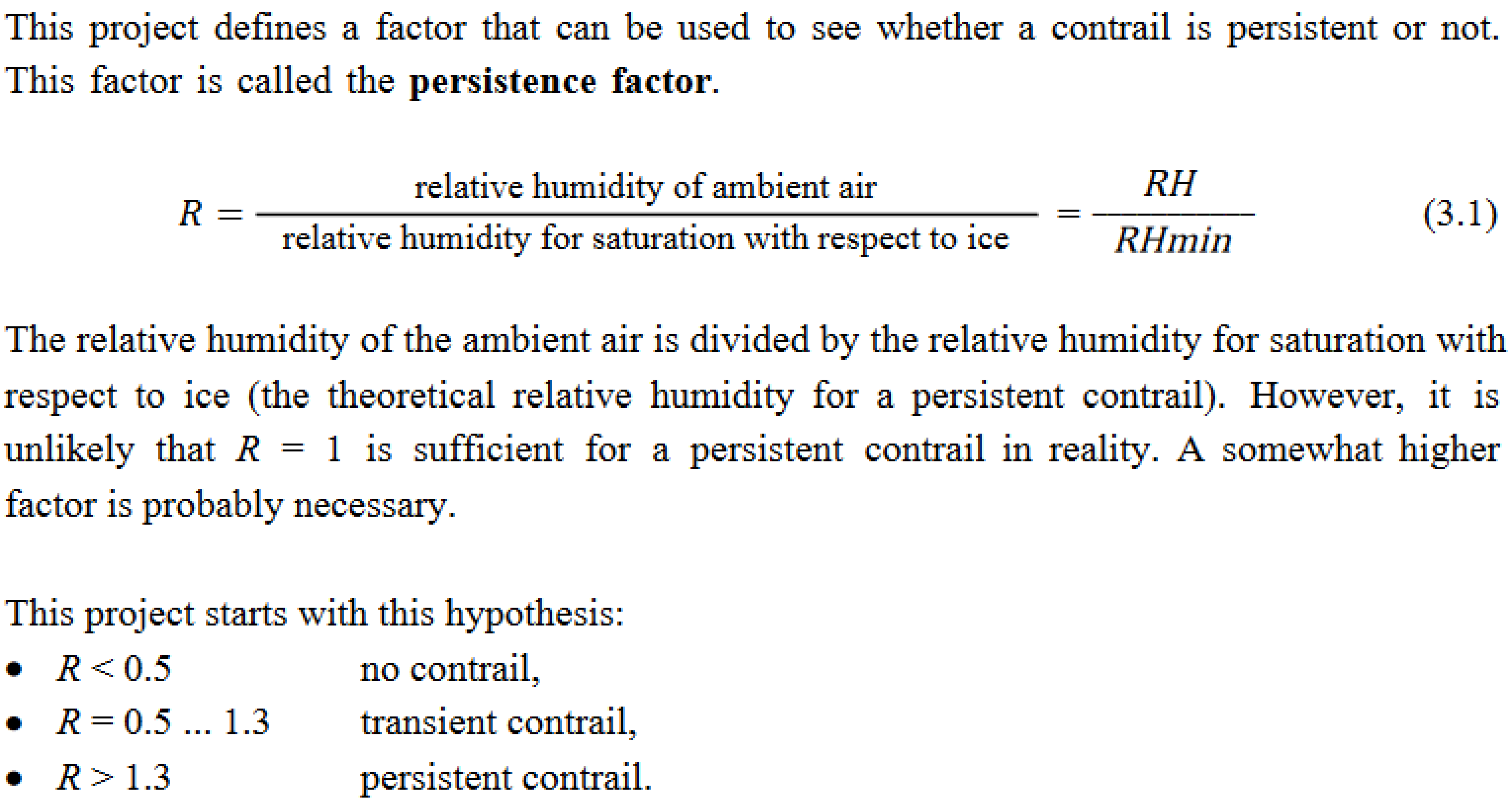
Evaluation of the Schmidt-Appleman Diagram



The red cross is far left of the blue line (100% relative humidity).

A contrail is expected to form.

Definition of the Persistence Factor, *R*



This project defines a factor that can be used to see whether a contrail is persistent or not. This factor is called the **persistence factor**.

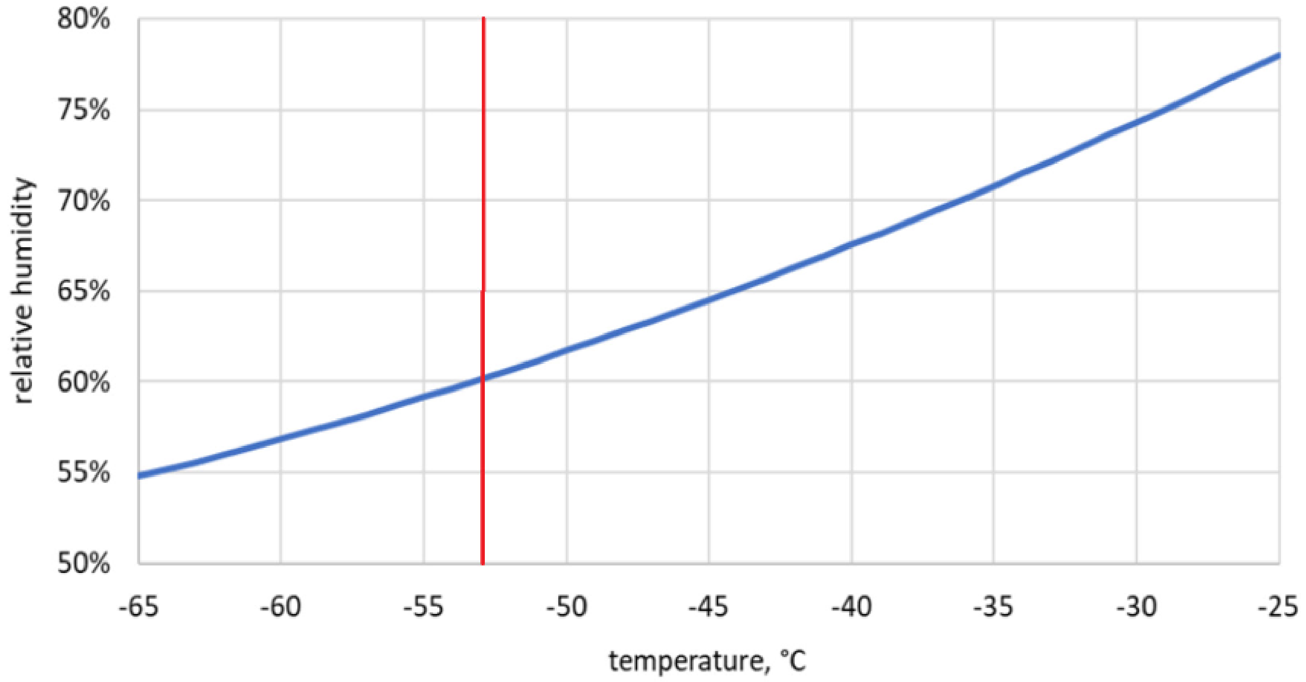
$$R = \frac{\text{relative humidity of ambient air}}{\text{relative humidity for saturation with respect to ice}} = \frac{RH}{RHmin} \qquad (3.1)$$

The relative humidity of the ambient air is divided by the relative humidity for saturation with respect to ice (the theoretical relative humidity for a persistent contrail). However, it is unlikely that $R = 1$ is sufficient for a persistent contrail in reality. A somewhat higher factor is probably necessary.

This project starts with this hypothesis:

$R < 0.5$	no contrail,
$R = 0.5 \ldots 1.3$	transient contrail,
$R > 1.3$	persistent contrail.

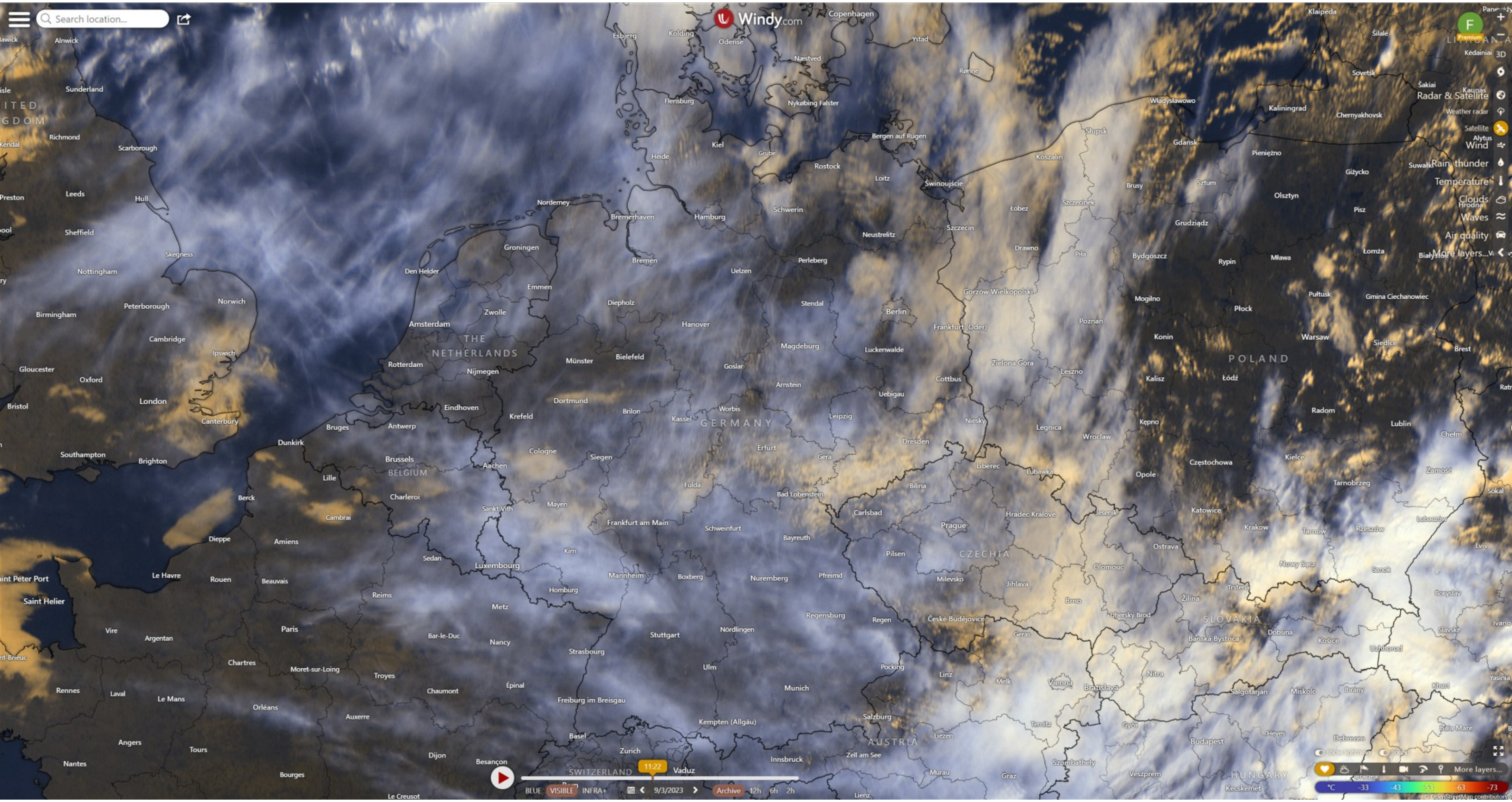
Evaluation of the Schmidt-Appleman Criterion



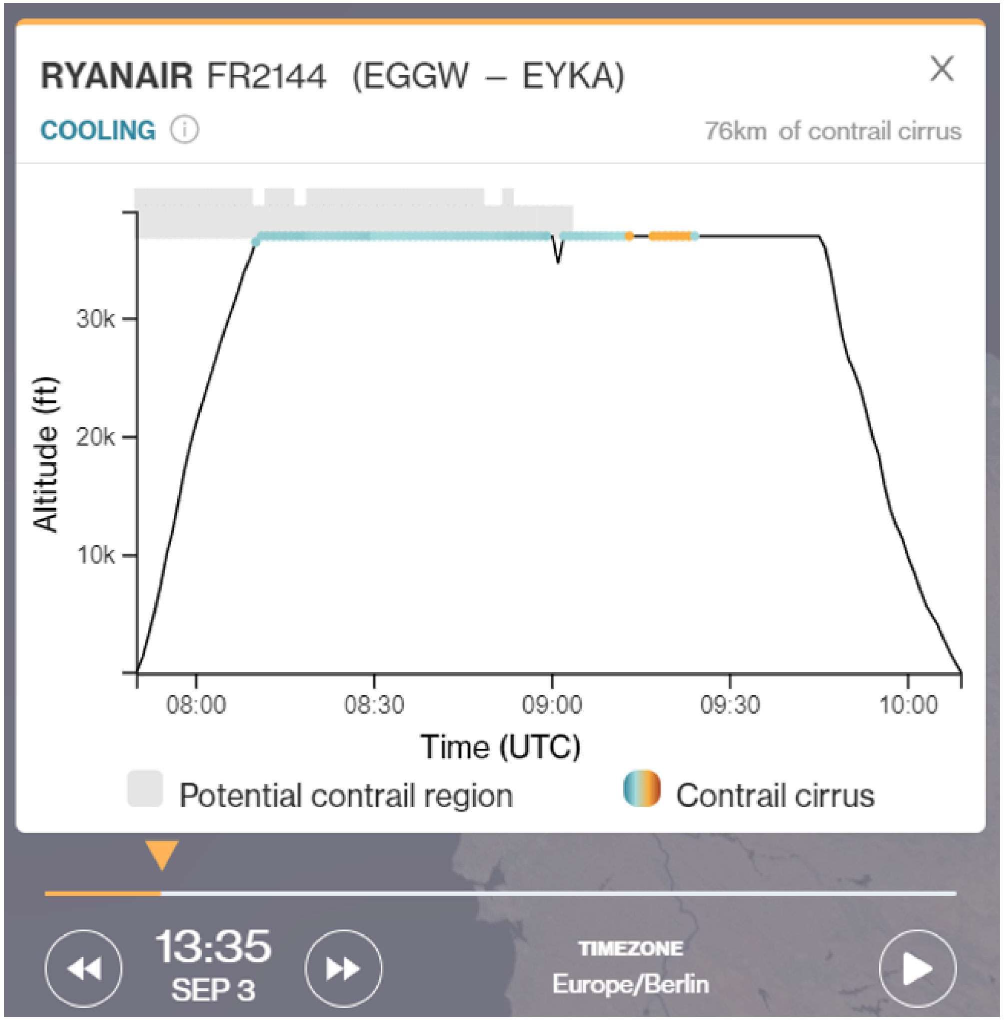
Minimum relative humidity for given temperature for persistent contrails to form.
If above the blue line persistent contrails are expected to form. Here

***R* = 100% / 60.2% = 1.66 => persistent contrail (survival longer than 5 min.)**

Weather Observation, Satellite Image



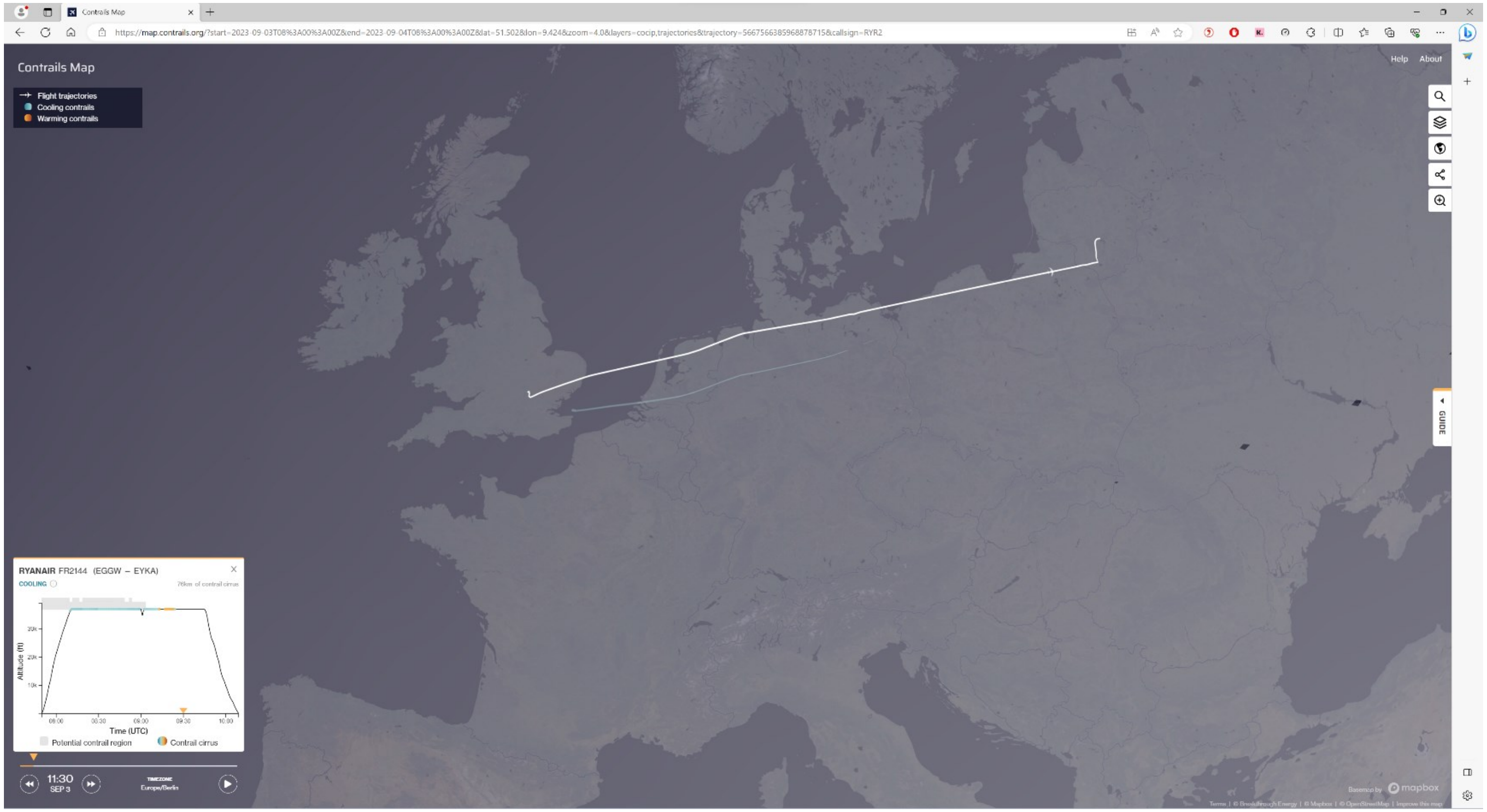
The Flight on contrails.org



AT 10:53 (08:53 UTC), the flight is passing just at the lower edge of a region with Potential Contrail Coverage (PCC).

At this time of the day (daytime) and the sky only partially covered with clouds, the **contrail is cooling**.

The Flight on contrails.org

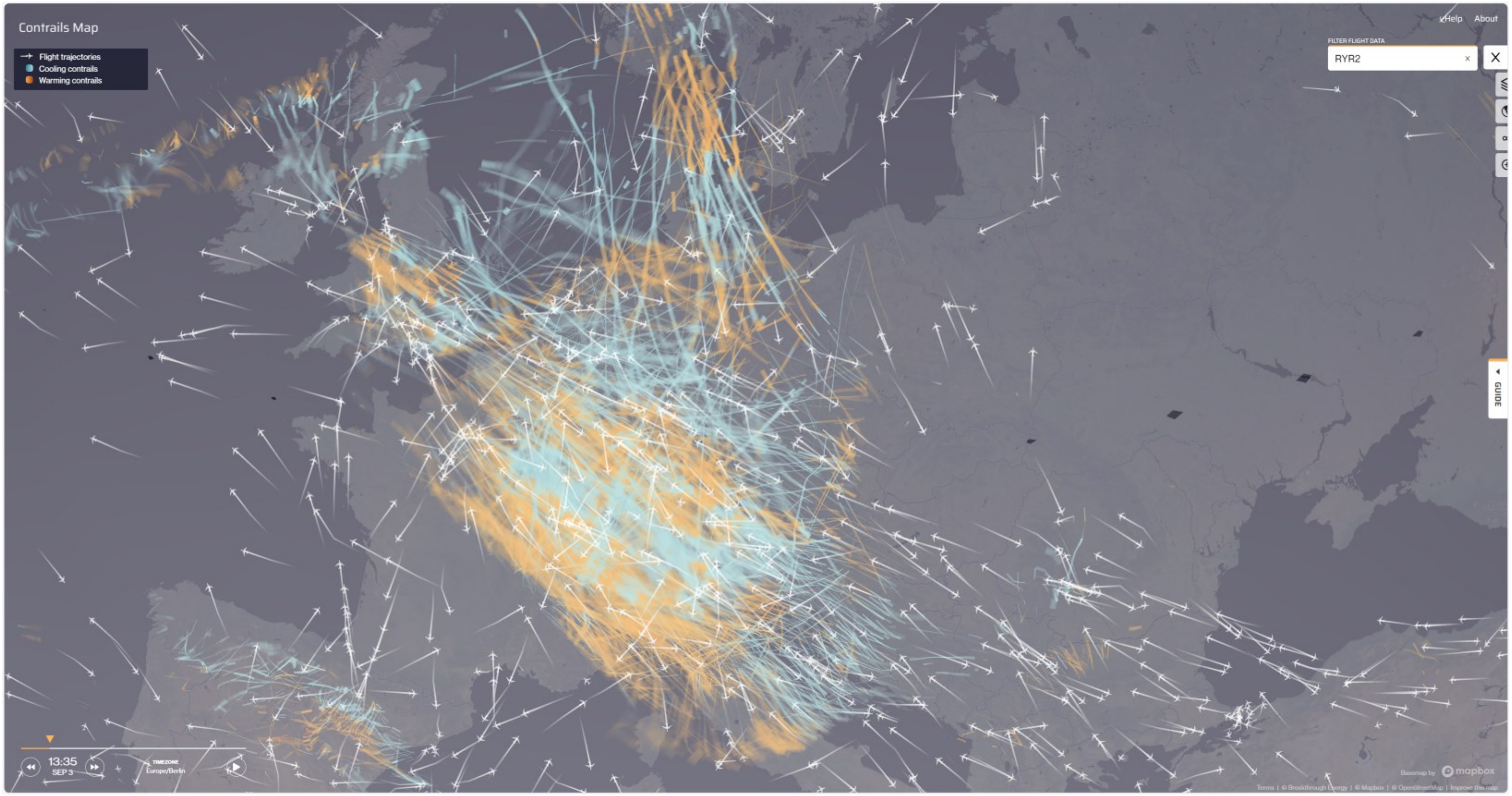


09:30 UTC: In a wind from the north (356°, 108 kt) the cooling contrail (blue) is drifting to the south.

The Flight on contrails.org

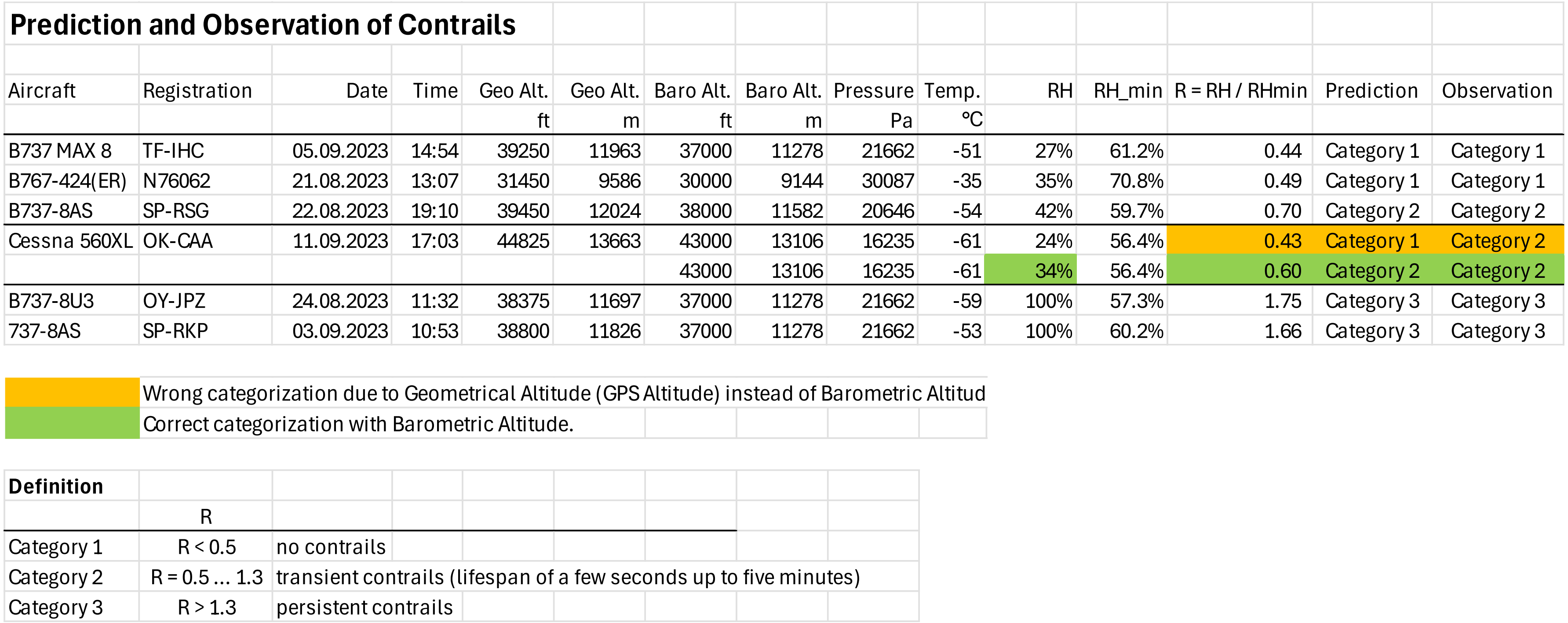
11:35 UTC: The contrail has drifted further south.

All Flights on contrails.org at 2023-09-03



11:35 UTC: All flights covered by contrails.org at this day and time. Some contrails are warming, some are cooling.

Observation & Prediction – Summary of 6 Flight



Prediction and Observation of Contrails

Aircraft	Registration	Date	Time	Geo Alt.	Geo Alt.	Baro Alt.	Baro Alt.	Pressure	Temp.	RH	RH_min	R = RH / RHmin	Prediction	Observation
				ft	m	ft	m	Pa	°C					
B737 MAX 8	TF-IHC	05.09.2023	14:54	39250	11963	37000	11278	21662	-51	27%	61.2%	0.44	Category 1	Category 1
B767-424(ER)	N76062	21.08.2023	13:07	31450	9586	30000	9144	30087	-35	35%	70.8%	0.49	Category 1	Category 1
B737-8AS	SP-RSG	22.08.2023	19:10	39450	12024	38000	11582	20646	-54	42%	59.7%	0.70	Category 2	Category 2
Cessna 560XL	OK-CAA	11.09.2023	17:03	44825	13663	43000	13106	16235	-61	24%	56.4%	0.43	Category 1	Category 2
						43000	13106	16235	-61	34%	56.4%	0.60	Category 2	Category 2
B737-8U3	OY-JPZ	24.08.2023	11:32	38375	11697	37000	11278	21662	-59	100%	57.3%	1.75	Category 3	Category 3
737-8AS	SP-RKP	03.09.2023	10:53	38800	11826	37000	11278	21662	-53	100%	60.2%	1.66	Category 3	Category 3

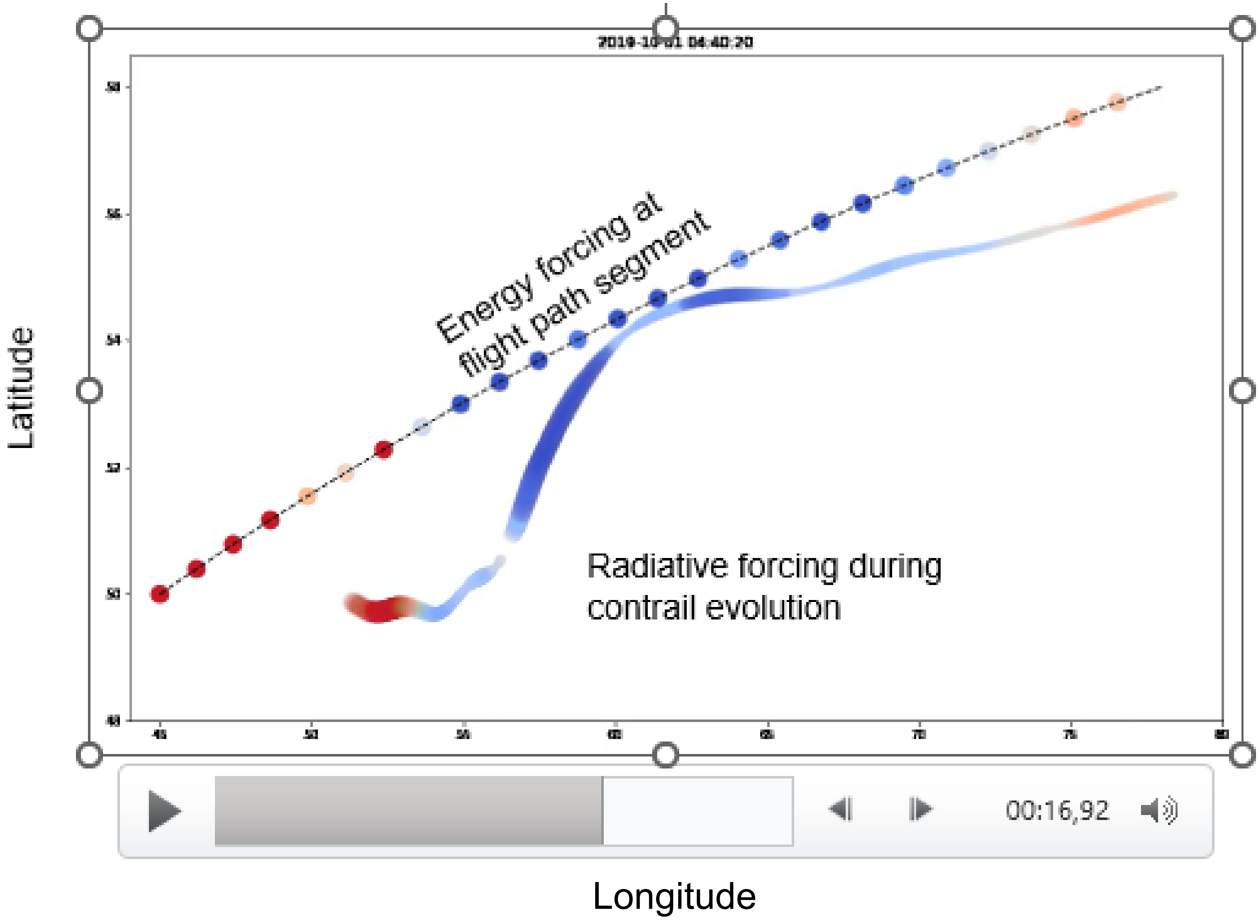
🟧	Wrong categorization due to Geometrical Altitude (GPS Altitude) instead of Barometric Altitud
🟩	Correct categorization with Barometric Altitude.

Definition		
	R	
Category 1	R < 0.5	no contrails
Category 2	R = 0.5 ... 1.3	transient contrails (lifespan of a few seconds up to five minutes)
Category 3	R > 1.3	persistent contrails

All 6 flight were classified correctly based on the Persistence Factor, *R*

DLR-Results

Contrail-Cirrus Prediction Tool (CoCiP)



Energy forcing at flight path segment

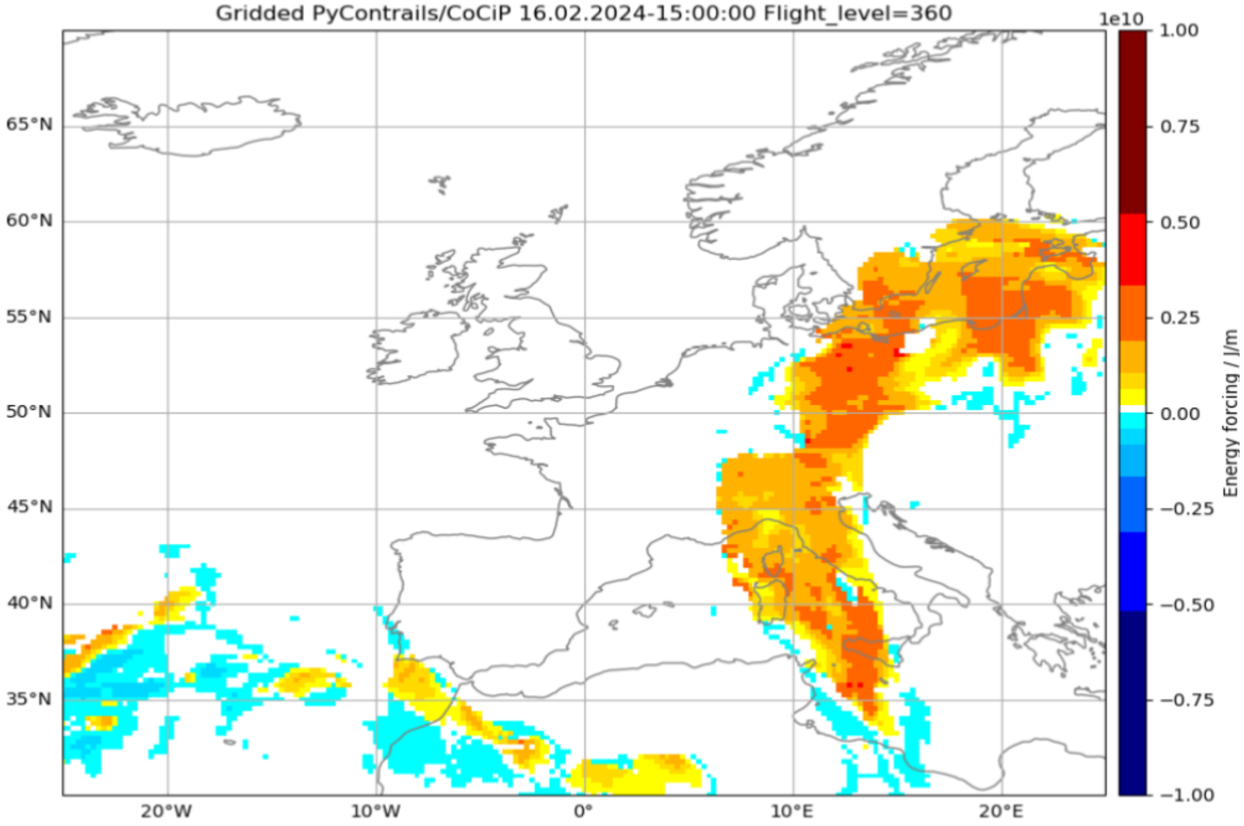
Radiative forcing during contrail evolution

https://py.contrails.org
(open source)

Flight on
10 Jan 2019, 0:00 to 6:00 h

Prediction of Regions with Contrails and Their Energy Forcing

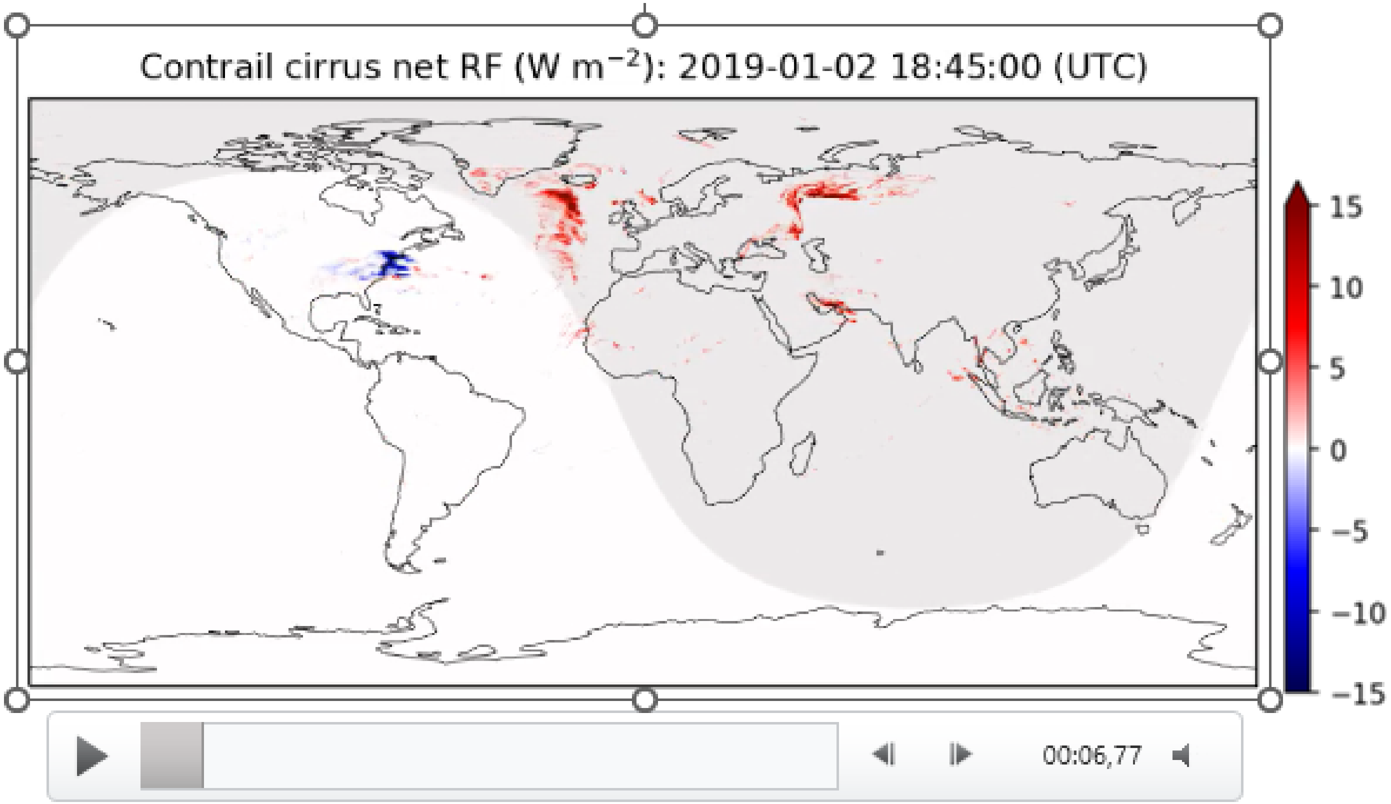
16.2.2024, FL 360, hourly prediction



One moment in time from a video showing the development of energy forcing of contrails in J/m.

Kirschler, DLR

Prediction of Regions with Contrails and Their Energy Forcing



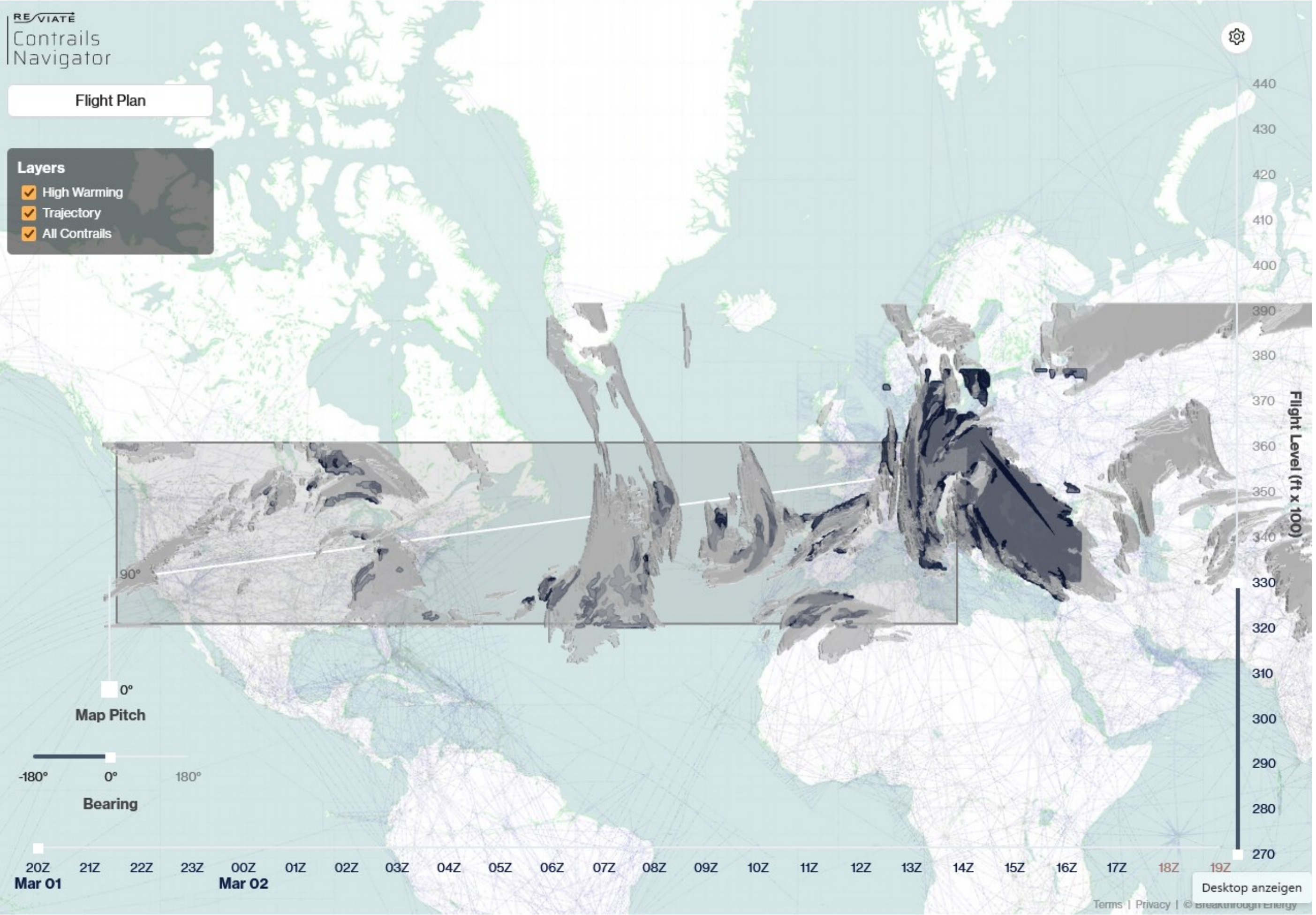
One moment in time from a video showing radiative forcing, RF of contrails in W/m². During the night, all contrails are warming. During the day, some contrails are cooling.

Teoh, Stettler, Imperial College; Shapiro, Breakthrough Energies; Schumann, Voigt, DLR

https://py.contrails.org (open source)

Contrail Management

Flight Planning with https://forecast.contrails.org



Here:

All contrails are shown in FL270 to FL330.

Free on request.

Flight Planning with https://forecast.contrails.org

Here:

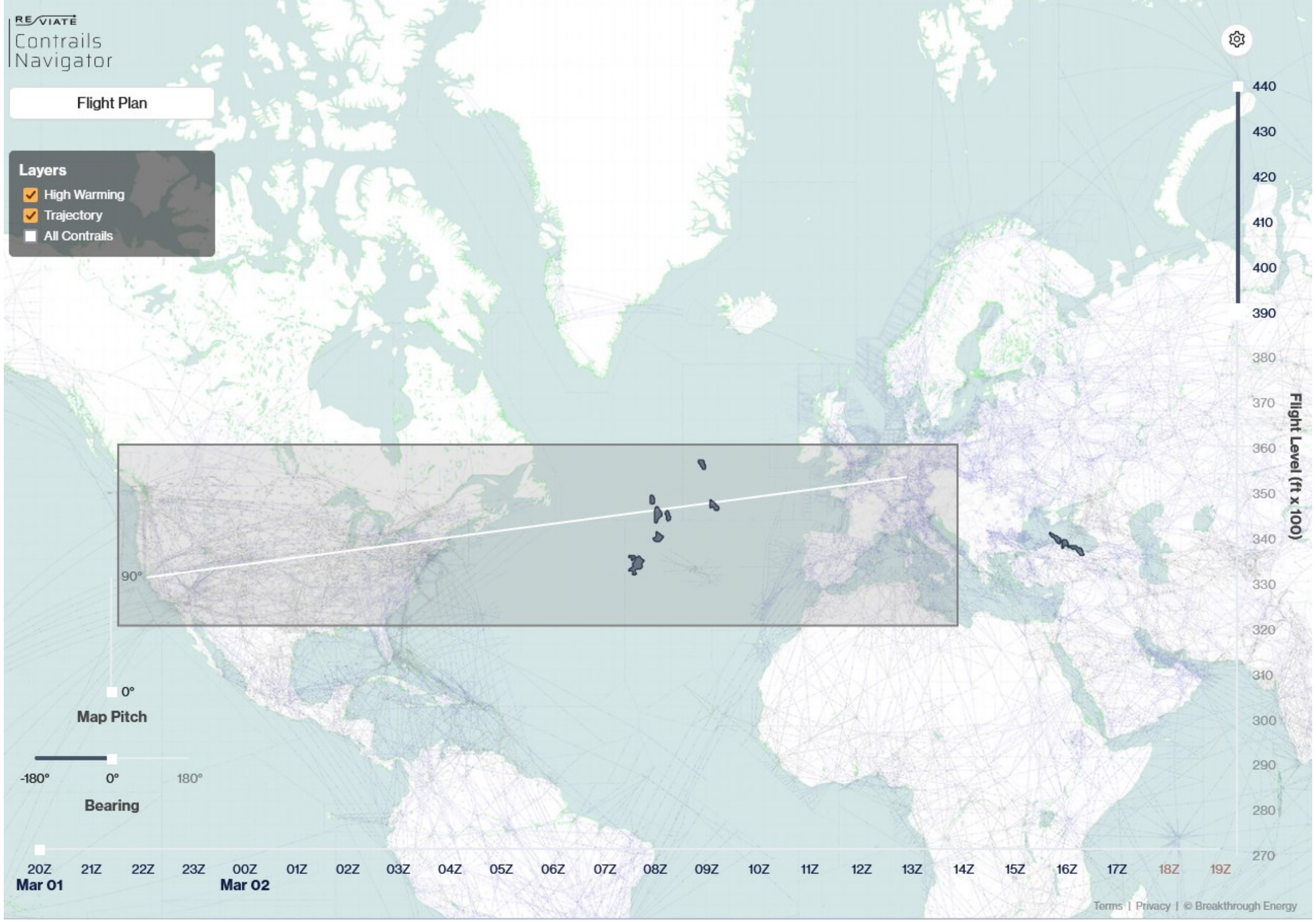
Only highly warming contrails are shown in FL270 to FL440.

Flight Planning with https://forecast.contrails.org

Here:

Only highly warming contrails are shown in FL330 to FL440.

Flight Planning with https://forecast.contrails.org

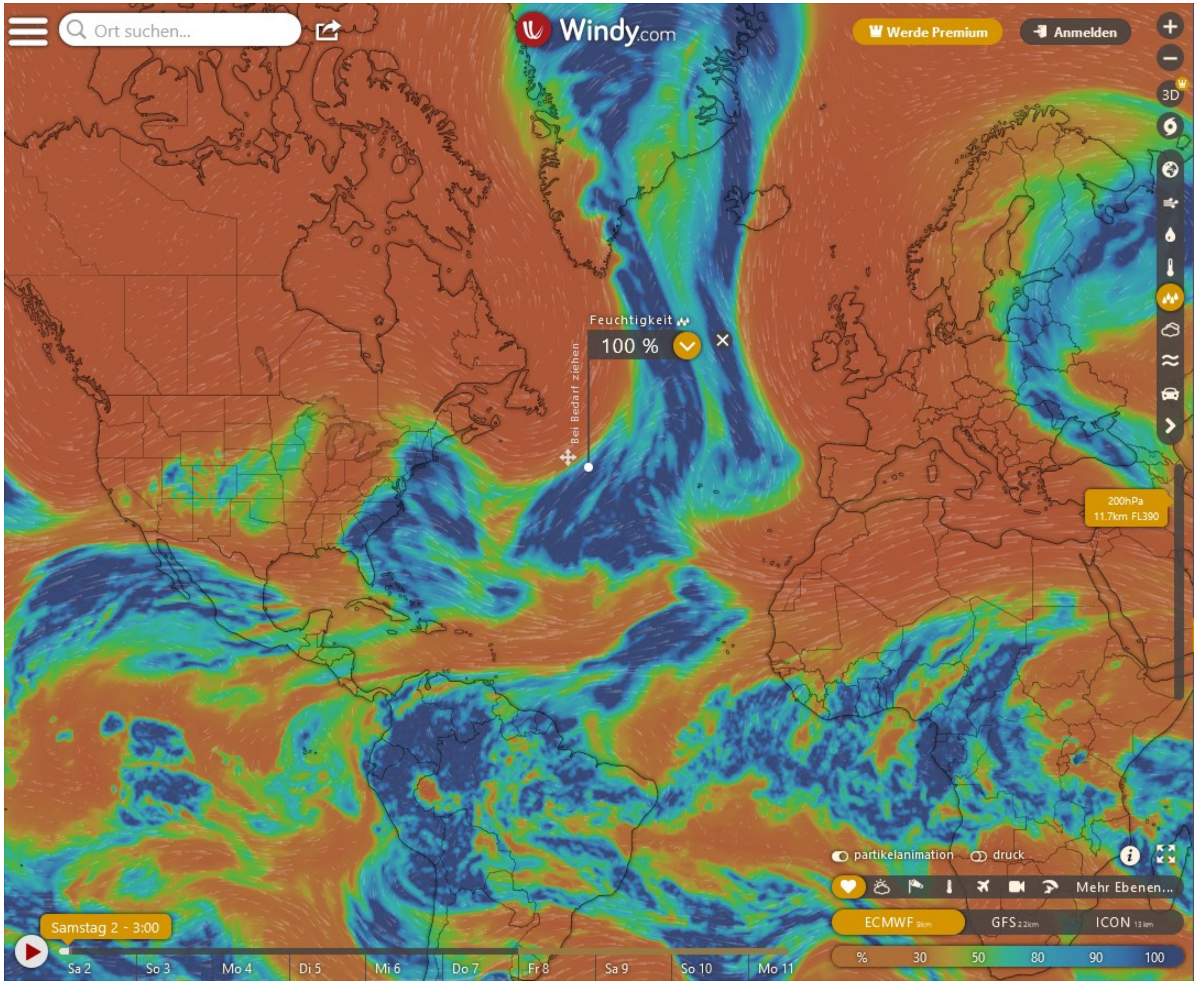


Here:

Only highly warming contrails are shown in FL390 to FL440.

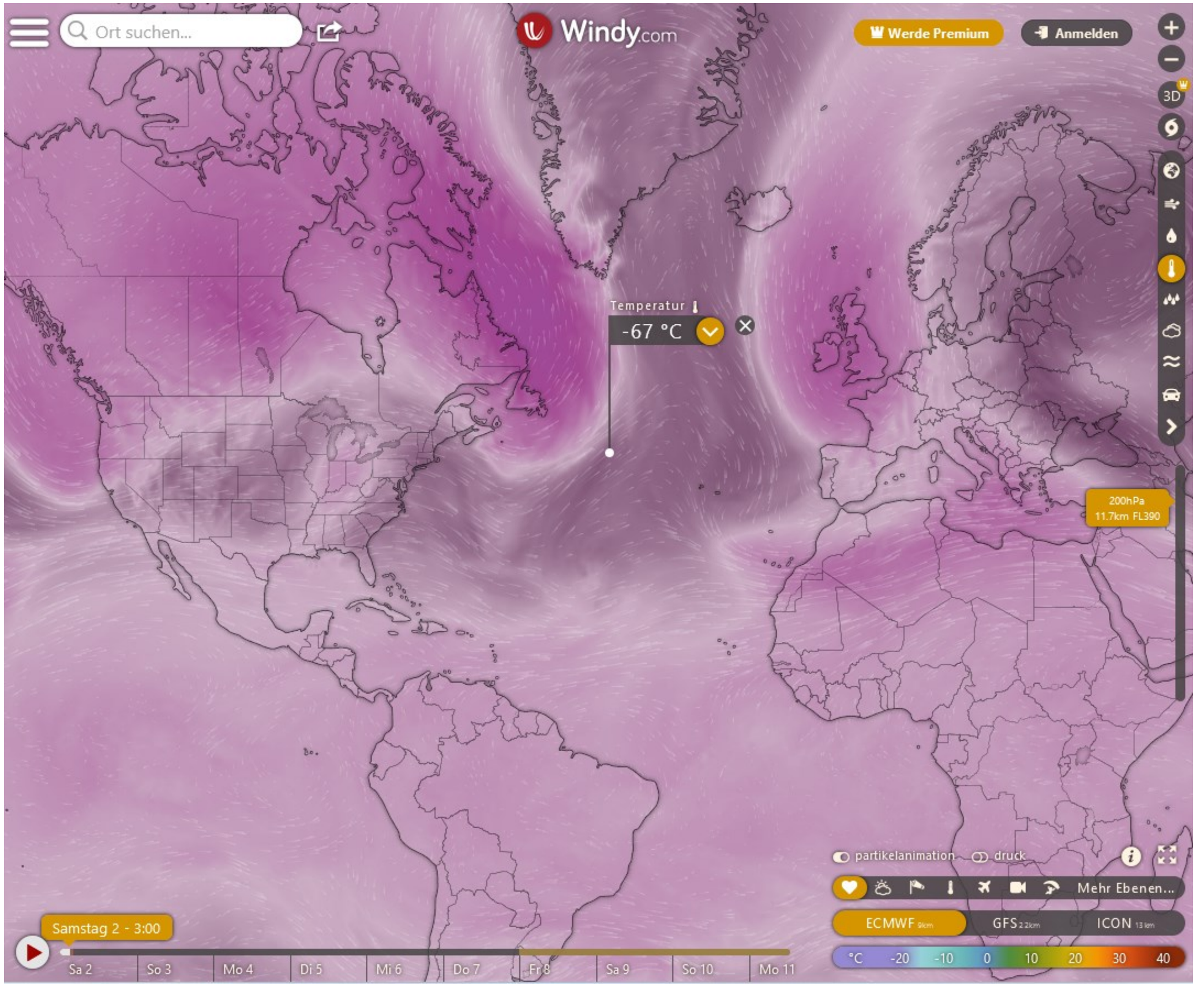
A business jet using these high flight levels would not need to be rerouted for contrail avoidance.

Flight Planning with https://www.windy.com



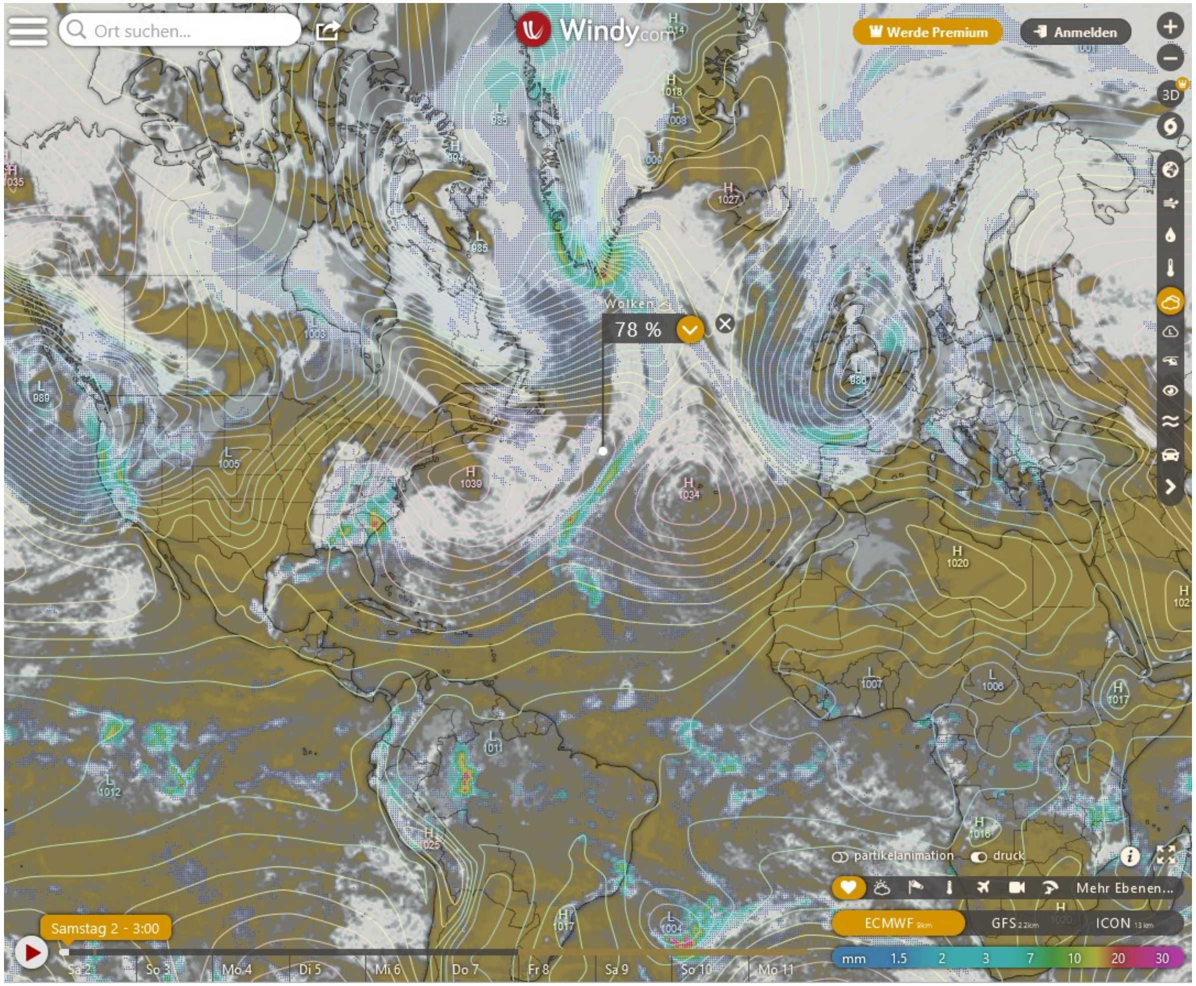
Relative humidity. Data from ECMWF and 7 other weather models. Forecast 5 days ahead. Vertical resolution is rather course: FL 100, 140, 180, 240, 300, 340, 390, and 450.

Flight Planning with https://www.windy.com



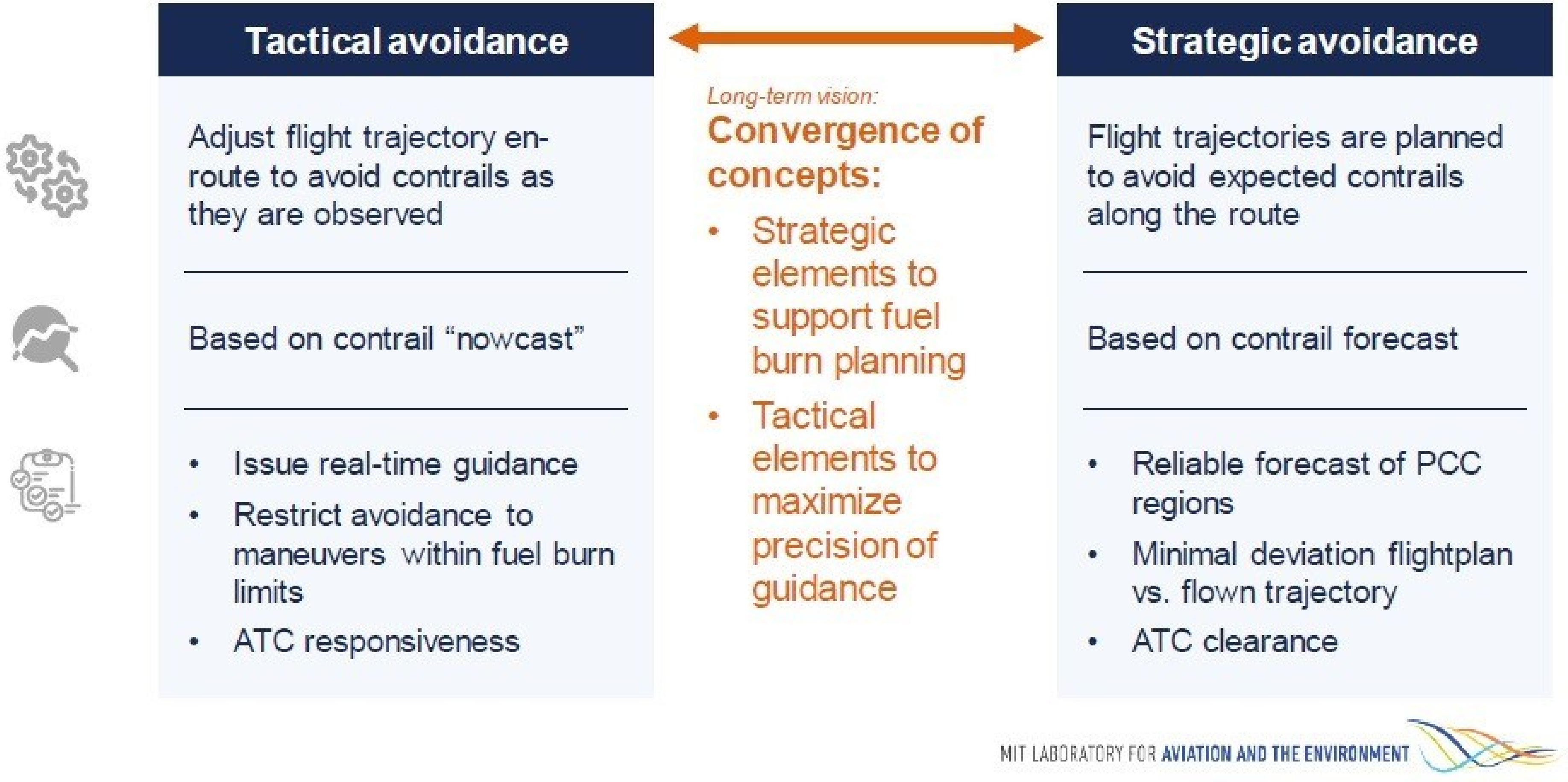
Temperature. Data from ECMWF and 5 other weather models. Forecast 5 days ahead. Vertical resolution is rather course: FL 100, 140, 180, 240, 300, 340, 390, and 450.

Flight Planning with https://www.windy.com



Clouds. Data from ECMWF and 7 other weather models. Forecast 5 days ahead. No vertical information. Cloud cover from brown (0%), via grey to white (100%). Precipitation (dots) from blue to purple according to scale.

Tactical versus Strategic Contrail Avoidance



Tactical avoidance	Strategic avoidance
Adjust flight trajectory en-route to avoid contrails as they are observed	Flight trajectories are planned to avoid expected contrails along the route
Based on contrail "nowcast"	Based on contrail forecast
• Issue real-time guidance • Restrict avoidance to maneuvers within fuel burn limits • ATC responsiveness	• Reliable forecast of PCC regions • Minimal deviation flightplan vs. flown trajectory • ATC clearance

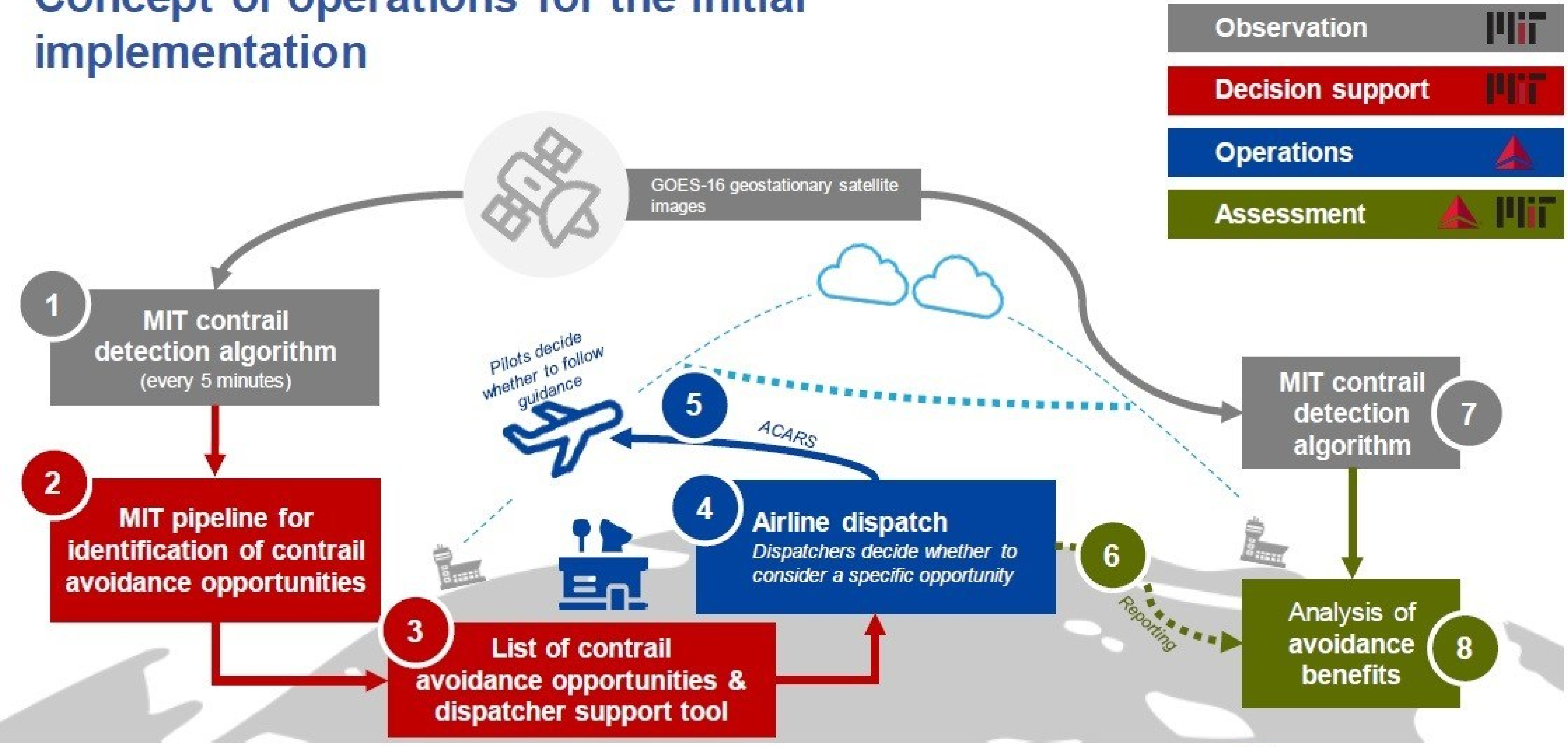
Long-term vision:

Convergence of concepts:

- Strategic elements to support fuel burn planning
- Tactical elements to maximize precision of guidance

MIT LABORATORY FOR **AVIATION AND THE ENVIRONMENT**

Concept of operations for the initial implementation



Observation

Decision support

Operations

Assessment

GOES-16 geostationary satellite images

1 MIT contrail detection algorithm (every 5 minutes)

2 MIT pipeline for identification of contrail avoidance opportunities

3 List of contrail avoidance opportunities & dispatcher support tool

4 Airline dispatch

Dispatchers decide whether to consider a specific opportunity

5

Pilots decide whether to follow guidance

ACARS

6

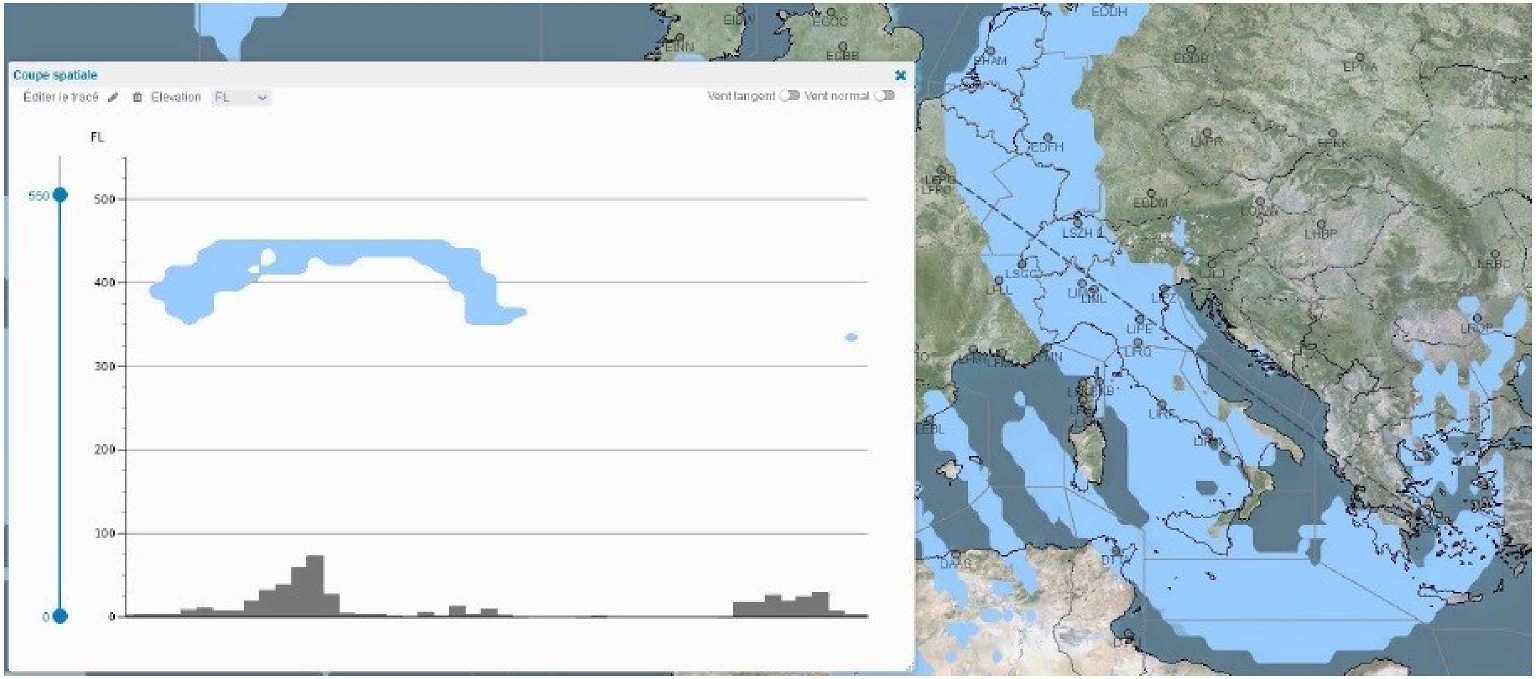
Reporting

7 MIT contrail detection algorithm

8 Analysis of avoidance benefits

Meteo France: Cross Section along Flight with ISSR (blue)

WIMCOT - Demonstration



Forecast for 04/09/2023 at 10UTC
From 03/09/2023 12UTC
Cross section from Paris to Athens

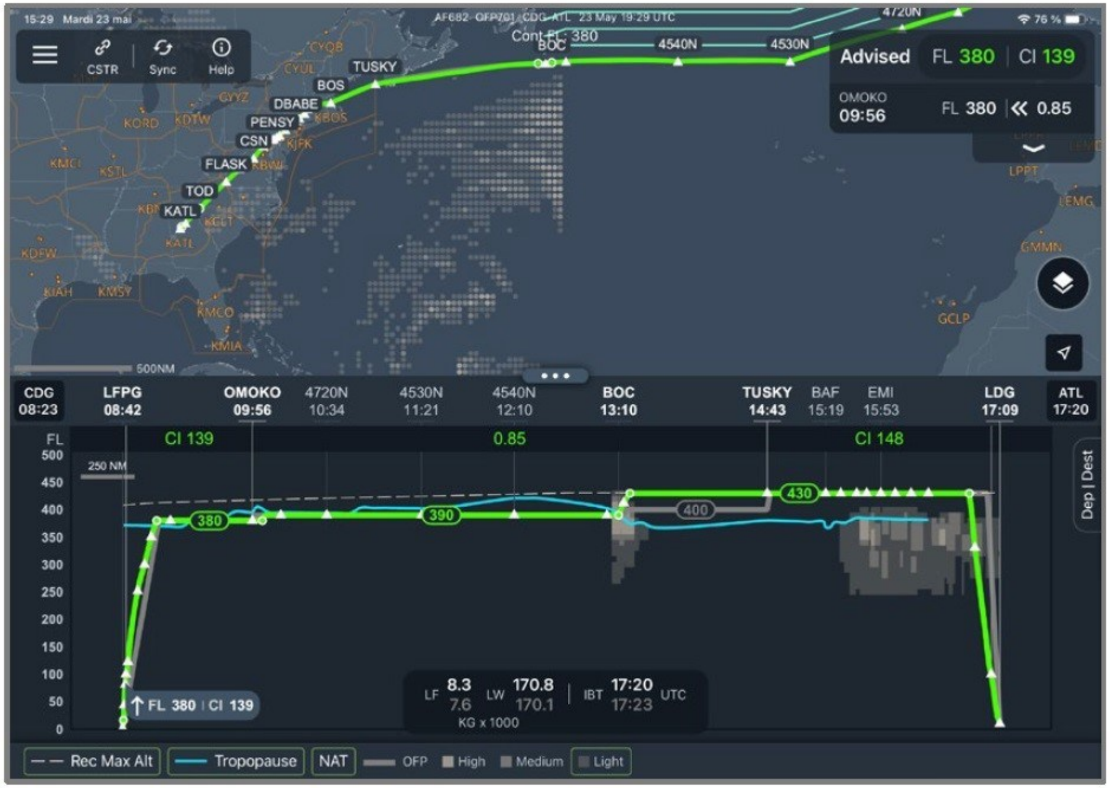
🟦 Risk area

This is only a demo for research.

Pace, Germany

https://pace.txtgroup.com

SHARE CONTRAILS RISK AREAS WITH PILOTS

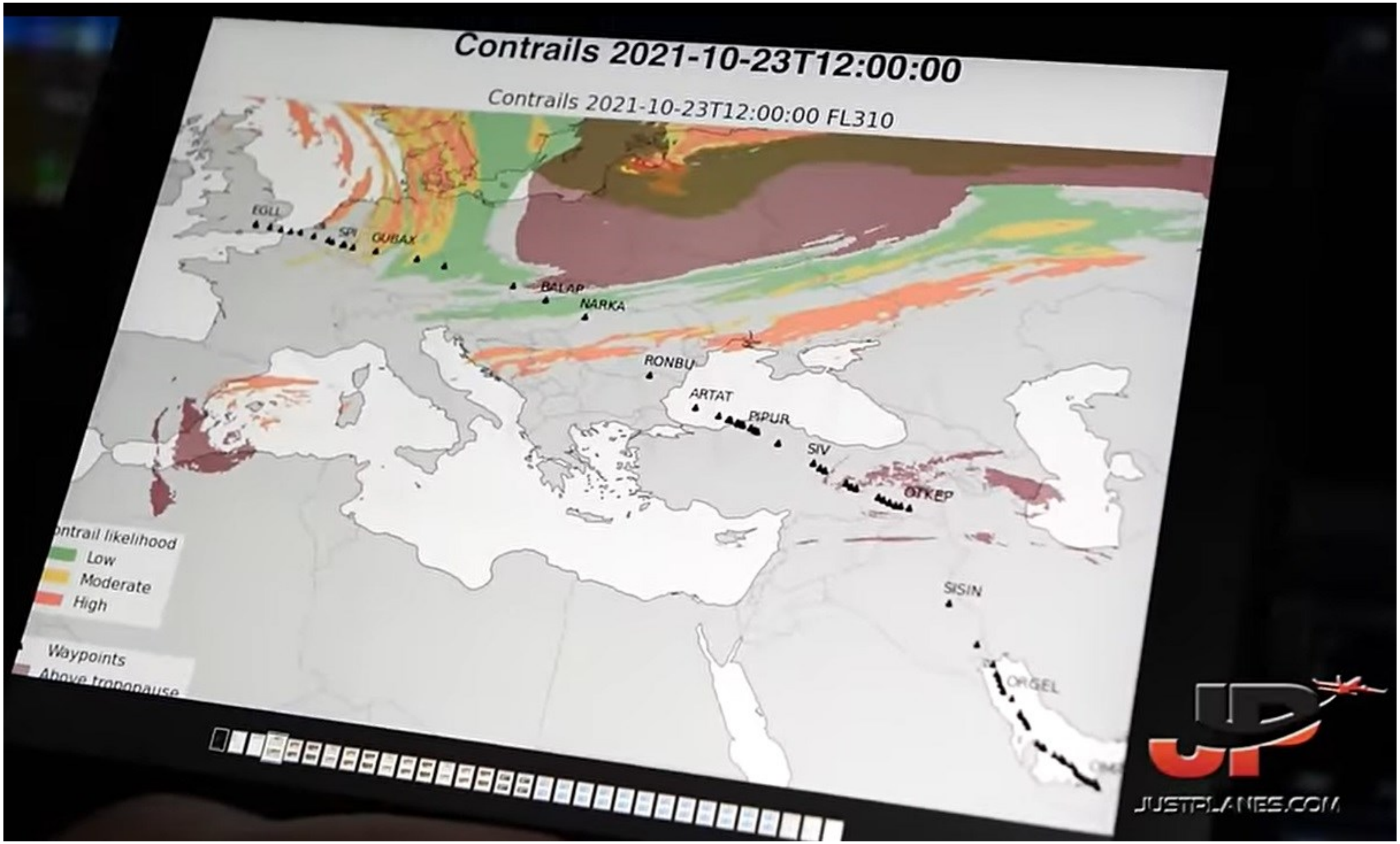


Pacelab FPO•SR combines lateral optimization capabilities with vertical flight profile optimization. Integration of weather (wind, turbulence) and ATC restrictions. Collaborative crew-dispatch decision-making. No contrail management. Electronic Flight Bag (EFB) for crew.

This is only a demo for research.

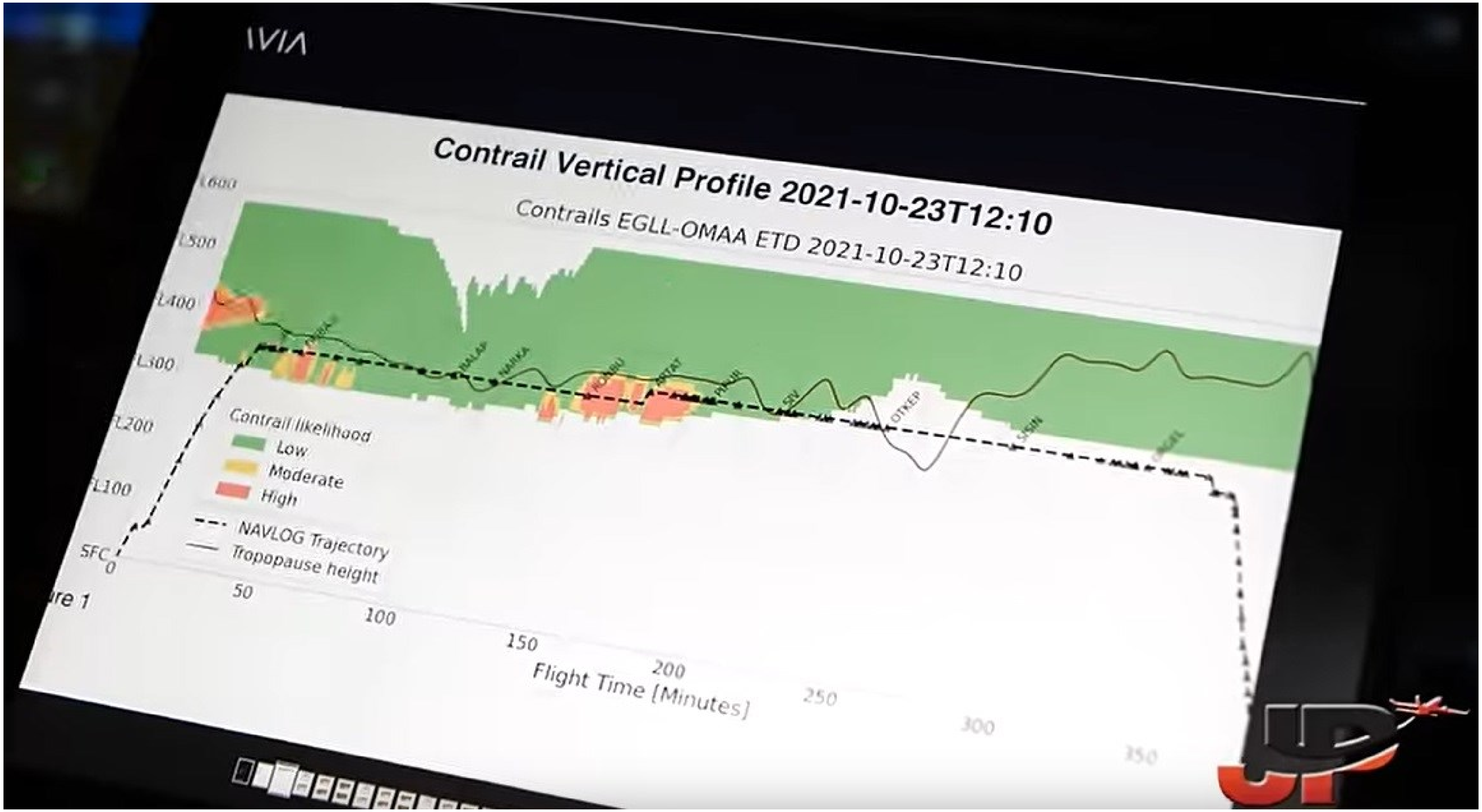
SATAVIA, UK and Etihad

https://satavia.com



https://youtu.be/r5tH2BsyMpE

SATAVIA, UK and Etihad



https://youtu.be/r5tH2BsyMpE

SATAVIA, UK

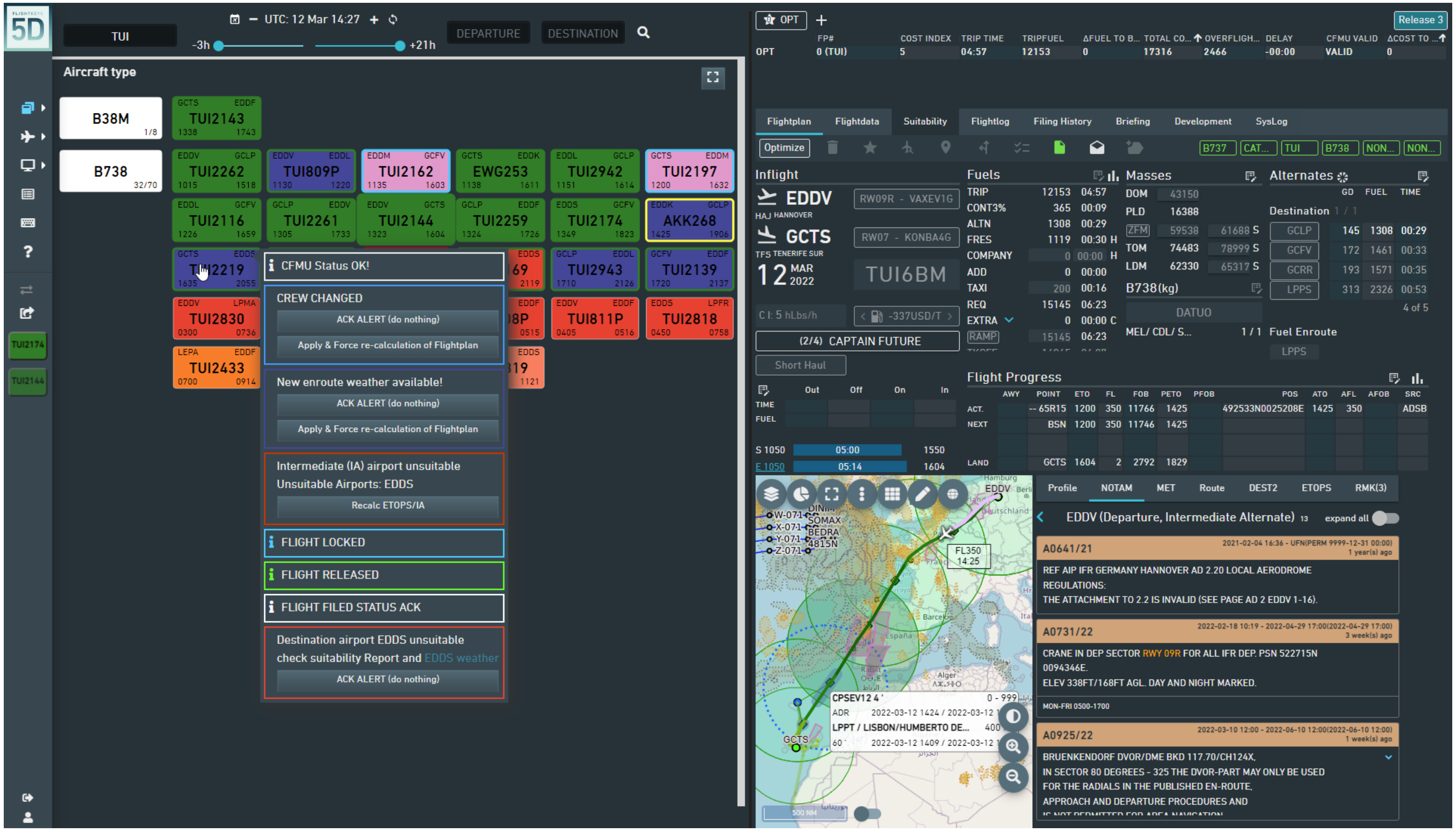
SATAVIA CEO, Dr. Adam Durant: "As a software solution incorporating the excellent and decades-mature atmospheric science available to us, contrail management provides the airline sector with an immediate and tangible option to reduce the climate impact of flying. With the incentive provided by Gold Standard Certified Mitigation Outcome Units (CMOUs), **aviation could reduce its non-CO2 impact by perhaps 50% before 2030**. All we need is a willingness to adopt this approach, which importantly doesn't require any changes to regulation and **could be deployed at scale today**."

https://perma.cc/4RFA-EETB

DECISIONX :NETZERO
SATAVIA

FlightKeys

https://www.flightkeys.com



FP#	COST INDEX	TRIP TIME	TRIPFUEL	ΔFUEL TO B...	TOTAL CO...	OVERFLIGH...	DELAY	CFMU VALID	ΔCOST TO ...
0 (TUI)	5	04:57	12153	0	17316	2466	-00:00	VALID	0

Fuels		
TRIP	12153	04:57
CONT3%	365	00:09
ALTN	1308	00:29
FRES	1119	00:30 H
COMPANY	0	00:00 H
ADD	0	00:00
TAXI	200	00:16
REQ	15145	06:23
EXTRA	0	00:00 C
RAMP	15145	06:23

Masses			
DOM	43150		
PLD	16388		
ZFM	59538	61688 S	
TOM	74483	78999 S	
LDM	62330	65317 S	

Alternates	GD	FUEL	TIME
GCLP	145	1308	00:29
GCFV	172	1461	00:33
GCRR	193	1571	00:35
LPPS	313	2326	00:53

CFMU Status OK!

CREW CHANGED

ACK ALERT (do nothing)

Apply & Force re-calculation of Flightplan

New enroute weather available!

ACK ALERT (do nothing)

Apply & Force re-calculation of Flightplan

Intermediate (IA) airport unsuitable
Unsuitable Airports: EDDS

Recalc ETOPS/IA

FLIGHT LOCKED

FLIGHT RELEASED

FLIGHT FILED STATUS ACK

Destination airport EDDS unsuitable
check suitability Report and EDDS weather

ACK ALERT (do nothing)

EDDV (Departure, Intermediate Alternate) 13 expand all

A0641/21 2021-02-04 16:36 - UFN(PERM 9999-12-31 00:00) 1 year(s) ago

REF AIP IFR GERMANY HANNOVER AD 2.20 LOCAL AERODROME REGULATIONS:
THE ATTACHMENT TO 2.2 IS INVALID (SEE PAGE AD 2 EDDV 1-16).

A0731/22 2022-02-18 10:19 - 2022-04-29 17:00(2022-04-29 17:00) 3 week(s) ago

CRANE IN DEP SECTOR RWY 09R FOR ALL IFR DEP. PSN 522715N 0094346E.
ELEV 338FT/168FT AGL. DAY AND NIGHT MARKED.

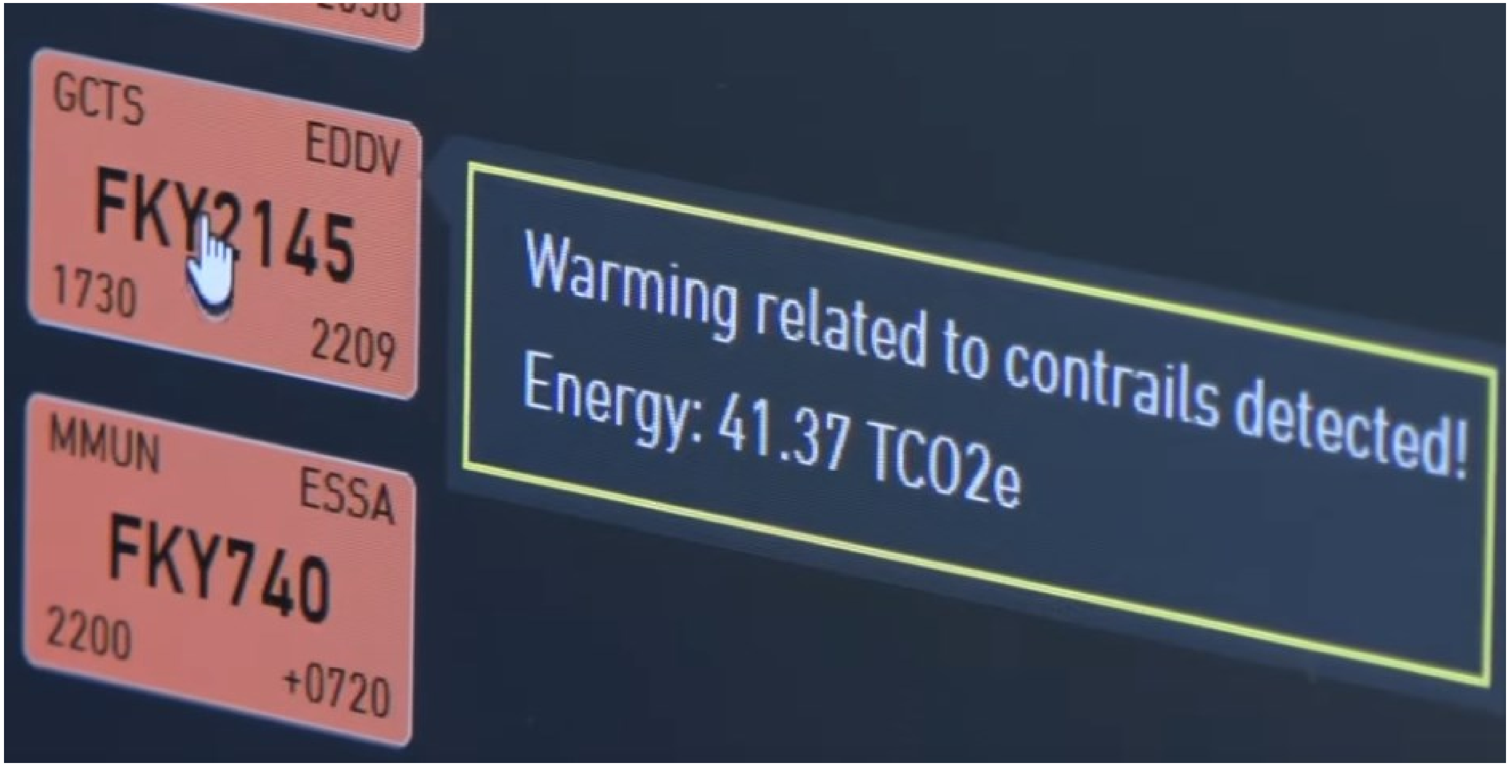
MON-FRI 0500-1700

A0925/22 2022-03-10 12:00 - 2022-06-10 12:00(2022-06-10 12:00) 1 week(s) ago

BRUENKENDORF DVOR/DME BKD 117.70/CH124X,
IN SECTOR 80 DEGREES - 325 THE DVOR-PART MAY ONLY BE USED
FOR THE RADIALS IN THE PUBLISHED EN-ROUTE,
APPROACH AND DEPARTURE PROCEDURES AND

FlightKeys flight planning system "5D".

FlightKeys

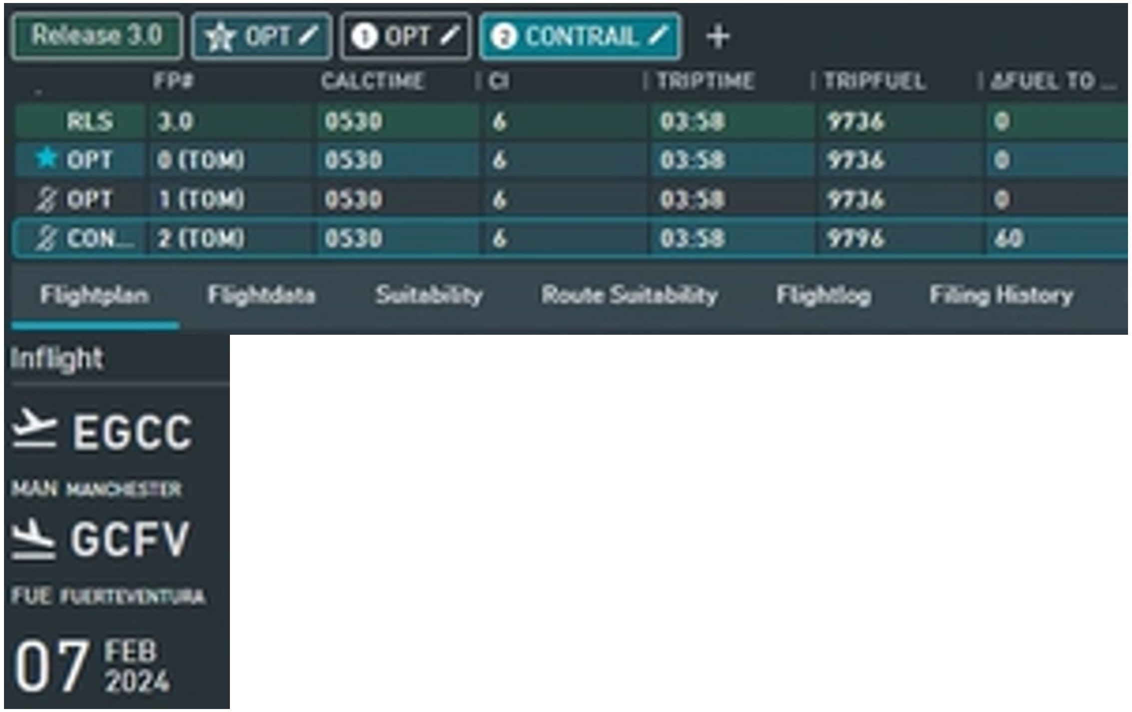


Warming related to contrails detected!
Energy: 41.37 TCO2e

FlightKeys flight planning system "5D" with new features for contrail avoidance.

https://youtu.be/HYJawLmiLS8

FlightKeys



	FP#	CALCTIME	CI	TRIPTIME	TRIPFUEL	ΔFUEL TO ...
RLS	3.0	0530	6	03:58	9736	0
★ OPT	0 (TOM)	0530	6	03:58	9736	0
OPT	1 (TOM)	0530	6	03:58	9736	0
CON...	2 (TOM)	0530	6	03:58	9796	60

Compared to the optimum flight plan, the contrail avoidance flight plan requires 60 kg more fuel (plus 0.6%). On average, contrail avoidance requires 0.11% more fuel (calculated by FlightKeys).

FlightKeys

FlightKeys flight planning system "5D" with new features for contrail avoidance. ISSRs are indicated in white. Lateral and vertical avoidance of ISSRs is possible.

https://youtu.be/HYJawLmiLS8

FlightKeys

FlightKeys flight planning system "5D" with new features for contrail avoidance.

The vertical flight profile on the right.

https://youtu.be/HYJawLmiLS8

FlightKeys

https://youtu.be/HYJawLmiLS8

Use of the Electronic Flight Bag (EFB) on a tablet in an Airbus A320 cockpit.

The EFB helps the pilot to make inflight adjustments to the flight (tactical contrail avoidance) if Air Traffic Control (ATC) allows.

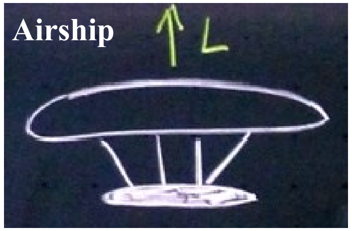
Comparing Modes of Transport

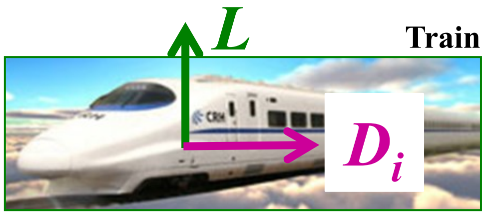
https://fytertech.com/eu/markets/transportation

Modes of Transport: Basics

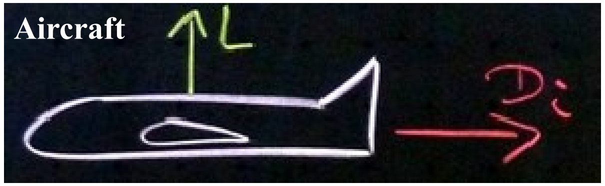
Force along the Way Due to Lift or Weight: Induced Drag, D_i

Vehicle shows less resistence / drag





Train



Helicopter

$$D_i = L / \infty = 0$$

$$D_i = L / 700$$

$$D_i = L / 40$$

$$D_i = T = L / 1$$

$$\boxed{E_i}$$

$$D = D_0 + D_i$$

↑

Force to push vehicle through the air (here ignored)

$$E = L / D$$

Def.: $E_i = L / D_i$

$$D_i = L / E_i$$

$D_i = L / 70$: Car on tarmac

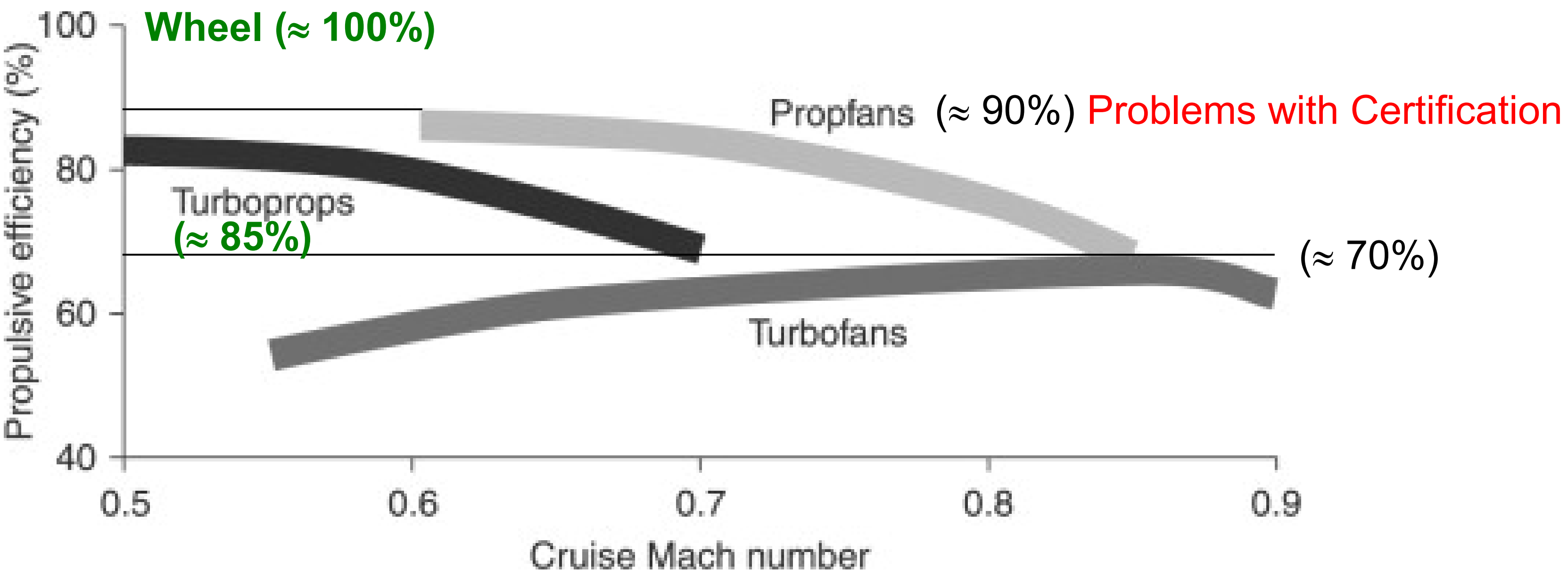
$D_i = L / 20$: Car on sand

D_i = induced Drag

L = Lift = Weight

T = Thrust

Propulsive Efficiency



https://www.sciencedirect.com/topics/engineering/propulsive-efficiency

Comparing Electro Mobility: From Energy to Approximate Emission

Type of Comparison	Kerosene / Diesel	Electricity / Battery
Energy (wrong)	$E = m_F \; H_L$	$E = E_{bat} / \eta_{charge}$
Max. Exergy (not good)	$B_{max} = \eta_C \; H_L \; m_F$	$B_{max} = E$
Exergy (ok)	$B = \eta_{GT} \; H_L \; m_F$	$B = \eta_{EM} \; E$
Primary Energy (better)	$E_{prim} = 1.1 \, H_L \; m_F$	$E_{prim} = k_{PEF} \; E$
CO2 (without altitude effect)	$m_{CO2} = 3.15 \cdot 1.1 \, m_F$	$m_{CO2} = 3.15 \, x_{ff} \; E_{prim} / H_L$
Equivalent CO2 (good, simple)	$m_{CO2,eq} = m_{CO2}(k_{RFI} + 0.1)$	$m_{CO2,eq} = m_{CO2}$

$H_L = 43 \text{ MJ/kg} \qquad \eta_{charge} = 0.9$

Carnot Efficiency :

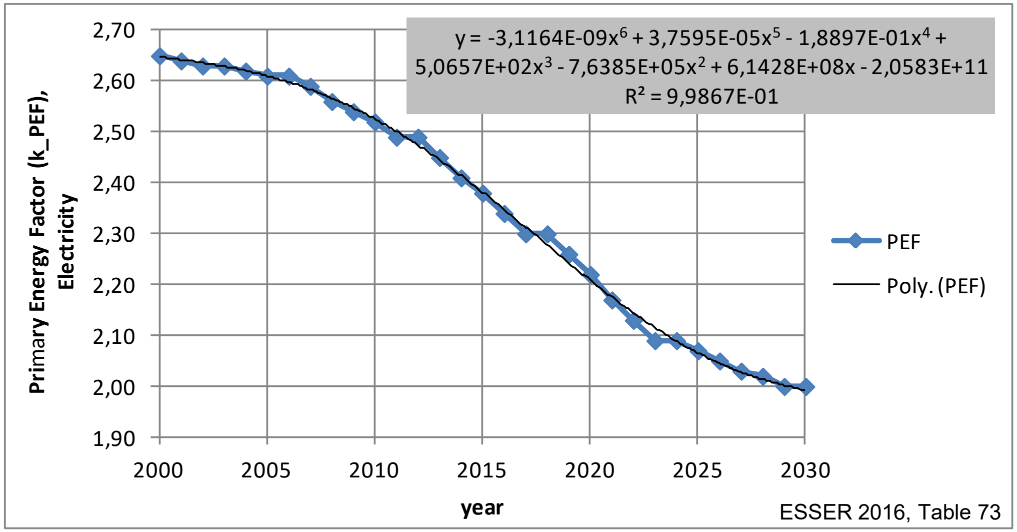
$\eta_C = 1 - T/(h)/T_{TET} =$

$= 1 - 216.65/1440 = 0.85$

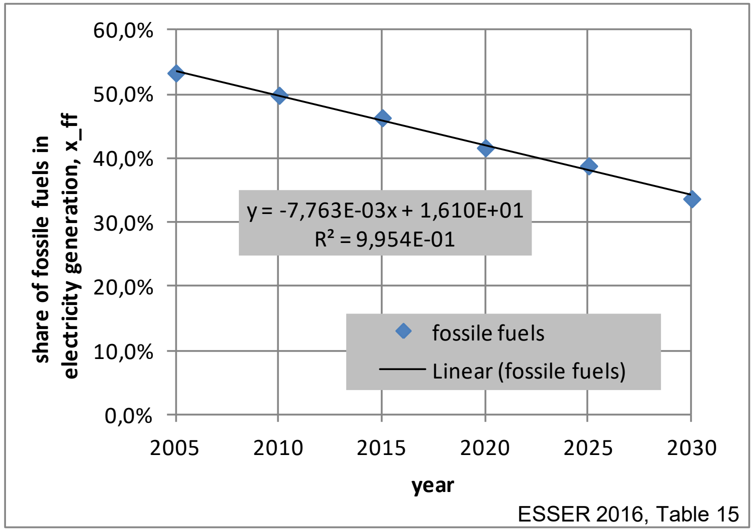
$\eta_{GT} = 0.35 \qquad \eta_{EM} = 0.9$

Radiative Forcing Index :

$k_{RFI} = 2.7 \quad (1.9 \ldots 4.7)$



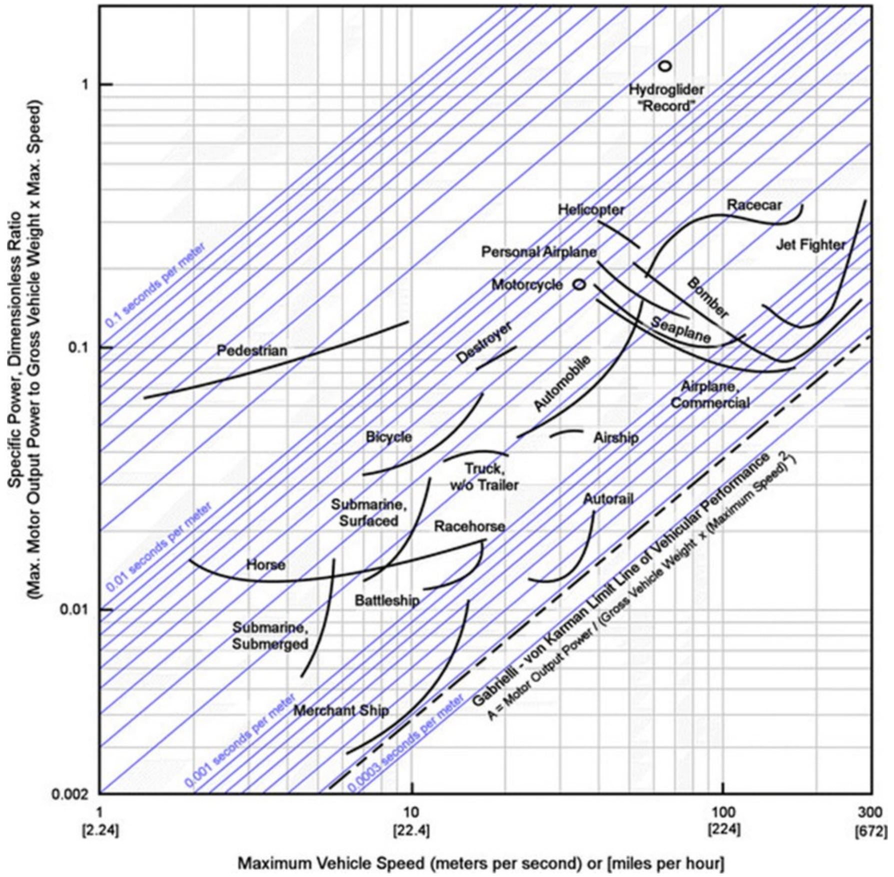
ESSER 2016, Table 73



ESSER 2016, Table 15

ESSER, Anke, SENSFUSS, Frank, 2016. *Evaluation of Primary Energy Factor Calculation Options for Electricity*. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (ISI). Available from: https://ec.europa.eu/energy/sites/ener/files/documents/final_report_pef_eed.pdf
Archived at: https://perma.cc/WMY7-QER4

The Original Karman-Gabrielli Diagram: "What Price Speed?"



Specific Power

$$\varepsilon = \frac{P}{W \cdot V}$$

Plot a „goodness“ parameter, G versus speed, V.

The "Figure of Merit", is the product of G · V

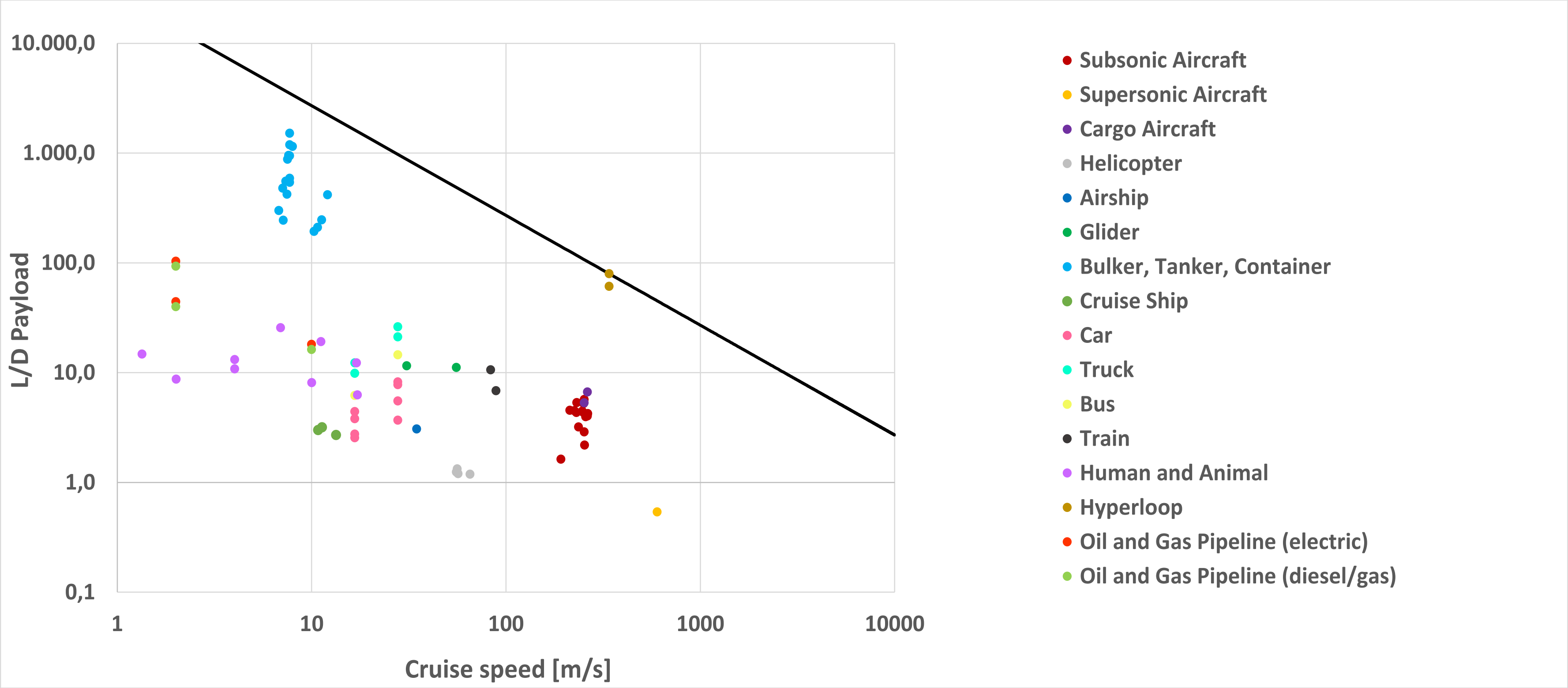
e. g.

$$a_{L/D} = L/D \cdot V$$

The original Karman-Gabrielli diagram as published by Trancossi (2016) in https://doi.org/10.1007/s40095-015-0160-6, plotting specific power versus maximum speed.

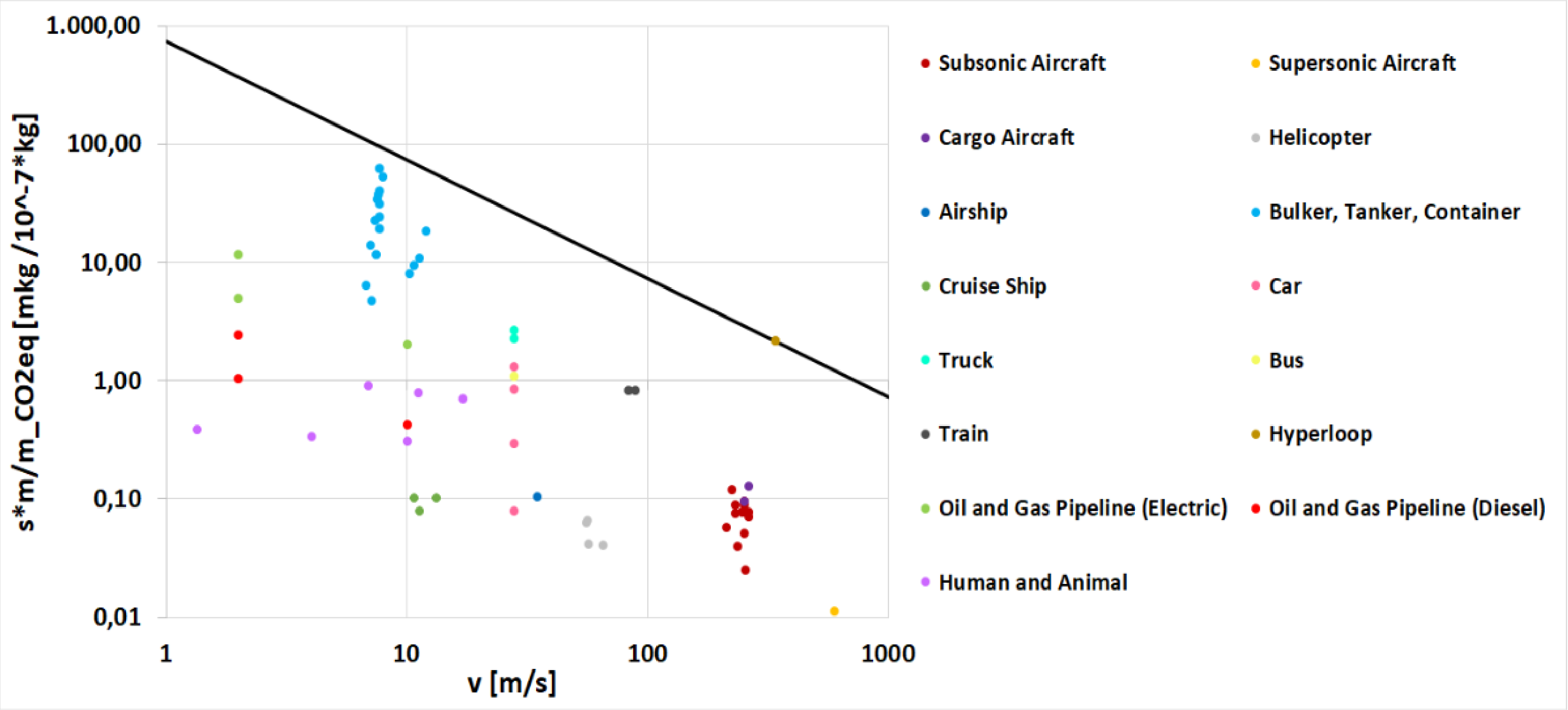
Bachelor Thesis by Dinda Andiani Putri
https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2023-04-20.015

Improved Karman-Gabrielli Diagram



The Karman-Gabrielli diagram plotting lift(for payload)-to-drag ratio, L/D_payload versus cruise speed, V .

Innovative Karman-Gabrielli Diagram



Karman-Gabrielli diagram plotting the inverse of equivalent CO2 mass per payload and range versus cruise speed, *V* .

Innovative Karman-Gabrielli Diagrams

Comprison of modes of transport:

- The diagonal line shows the best combinations of *G* and *V*.
- The diagonal line is defined by the hyper loop (passenger transport in tubes).
- Lowest drag or equivalent CO2 is achieved by cargo ships (bulker, tanker, container).
- Cruise ships perform badly.
- Aircraft are fast, medium in drag, but bad in equivalent CO2.
- High Speed Trains are ok when comparing *G* and *V*.
- Some cars are better than the train, but slower.
- Trucks are efficient.
- Lowest drag for land transportation is achieved by pipeline transport (with electric pumps), but it is very slow.
- Humans (and animals) are not very efficient. CO2 emissions are accepted, because they go along with training activities good for human health.

Comparison:
Aircraft – Car
Aircraft – Train

Short Range

Comparison of Transport Systems for Short Range: Aircraft – Car

- For a comparison with the car, one could assume a typical aircraft with 3 kg per seat and 100 km. However, we select the lower consumption of a modern short- and medium-haul aircraft for comparison. Accordingly, this is 1.7 kg per seat and 100 km if the aircraft is operated in its optimal flight route range. With the density of kerosene (0.8 kg/l), this is about 2.1 liters per seat and 100 km, but 2.7 liters per person and 100 km if the aircraft is only 80% occupied. A fully occupied car consumes significantly less per person than a fully occupied aircraft. However, if you are traveling alone in a car, then the plane would be better in terms of energy consumption. In the case of aircraft, however, the effect non-CO2 emissions must be taken into account by a factor of 3. **The car would then be better for the climate, even if it is only used by one person**.

Aircraft: 2.1 l/100 km and seat
=> Equally, a car could consume 8.4 l/100 km to 10.5 l/100 km (4 to 5 people in the car)
=> **a modern car is significantly better** (just based on fuel consumption).

Aircraft: 2.7 l/100 km and person (80% occupancy of the aircraft)
=> Equally, a car could emit equivalent to 8.1 l/100 km (factor: 3) due to non-CO2 effects
=> **a modern car is better, even with one person traveling**, if the non-CO2 emissions of the aircraft are considered.

My report in the Repository:
https://doi.org/10.48441/4427.225

Directly to the PDF:
https://purl.org/aero/RR2021-07-03

To the HTML:
https://www.fzt.haw-hamburg.de/pers/Scholz/Aero/AERO_PR_UmweltschutzLuftfahrt/Umweltschutz-in-der-Luftfahrt.html

HAW HAMBURG

Umweltschutz in der Luftfahrt – Hintergründe und Argumente zur aktuellen Diskussion

Dieter Scholz

2021

Empfohlene Zitierung:

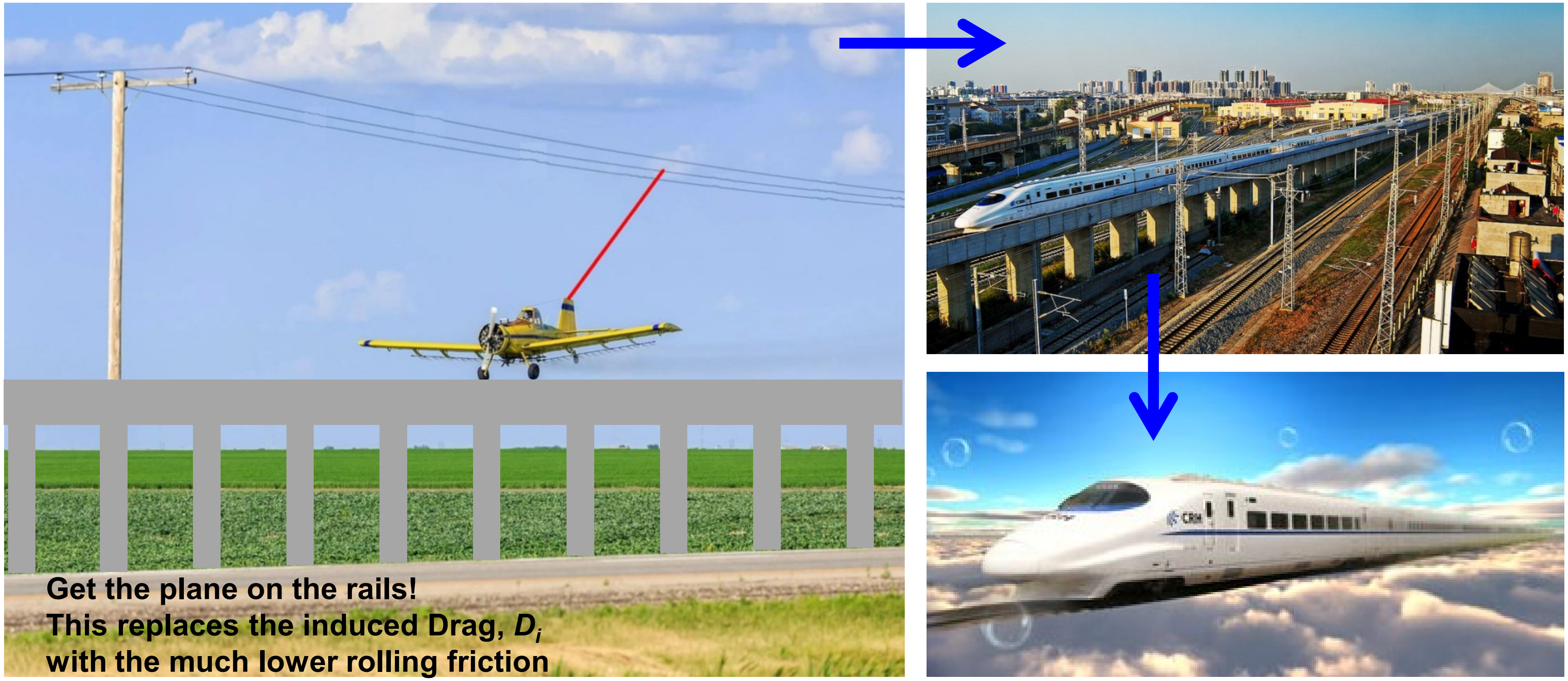
SCHOLZ, Dieter, 2021. *Umweltschutz in der Luftfahrt – Hintergründe und Argumente zur aktuellen Diskussion*. Bericht. Hochschule für Angewandte Wissenschaften Hamburg, Aircraft Design and Systems Group (AERO).

Zitierlink:

DOI: https://doi.org/10.48441/4427.225
Handle: https://hdl.handle.net/20.500.12738/11261

Short Range the Train is Better!

Electromobility that is operated on the grid is already successfully on rails!



Get the plane on the rails!
This replaces the induced Drag, D_i
with the much lower rolling friction

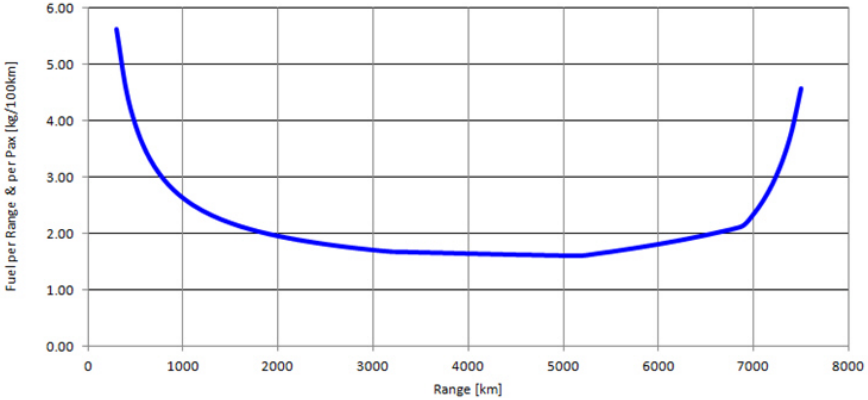
- **Aircraft**: Induced drag is drag due to lift = weight.
- **Train**: Rolling friction is caused by weight.
- Aircraft: For minimum drag: Induced drag is 50% of total resistance.
- For the same weight: Rolling friction from the train is 5% of the induced drag of the aircraft!
- This means: For the same weight: **Drag of the aircraft is reduced by 47.5%, on rails!**

Comparison of Transport Systems for Short Range: Aircraft – Train

- **The energy consumption of a train is low on route**. Energy for acceleration, which cannot be recovered or can only be partially recovered during **braking**, is crucial. The distance between the stations and the speed that is to be achieved between them will therefore be important. In the **tunnel**, consumption rises sharply. The consumption of the train can therefore actually only be specified for a train together with the route traveled. Despite these fundamental difficulties, an average consumption of 60 Wh per seat and km should be assumed here. The comparison does not take into account the fact that passengers have more space on the train. A comparison with the aircraft will only be possible when the primary energy used for the electrical energy of the train is calculated. This is the amount of energy (e.g. diesel) required to generate the electrical energy in the power plant. The electricity mix plays a role here. It is therefore the case that the conversion losses in the power plant have a negative impact on the train. The aircraft is struggling with these conversion losses in its own engine. For the aircraft, a typical 3 kg per seat and 100 km is assumed. Even for a modern aircraft this consumption is correct on short range (see below). **The primary energy consumption of the aircraft on short-haul routes will then be 2.8 times higher than that of the train.**

- Next, the **CO2 emissions are compared**. If the train is operated with the general **electricity mix**, it already runs with a lower fossil fuel content and the aircraft thus has 6.1 times higher CO2 emissions. The equivalent CO2 at cruising altitude is three times that of an airplane. In this example, **the aircraft has 18.3 times the environmental impact**. If the aircraft then compares with the train on extremely short distances, then the consumption of the aircraft may be higher than 3 kg per seat and 100 km and the comparison would be even more unfavorable for the aircraft. In this case, it would be helpful for the aircraft that the normal cruising altitude is not reached on short-haul flights and that the factor 3 for calculating the equivalent CO2 is reduced somewhat (to about 2). Then you would still have 12.2 times the environmental impact.

Calculations in:
SCHOLZ, Dieter, 2021c.
Energy Consumption, CO2, and Equivalent CO2 – Aircraft versus Train.
Data Sheet. Available from: https://doi.org/10.7910/DVN/QFG2SD



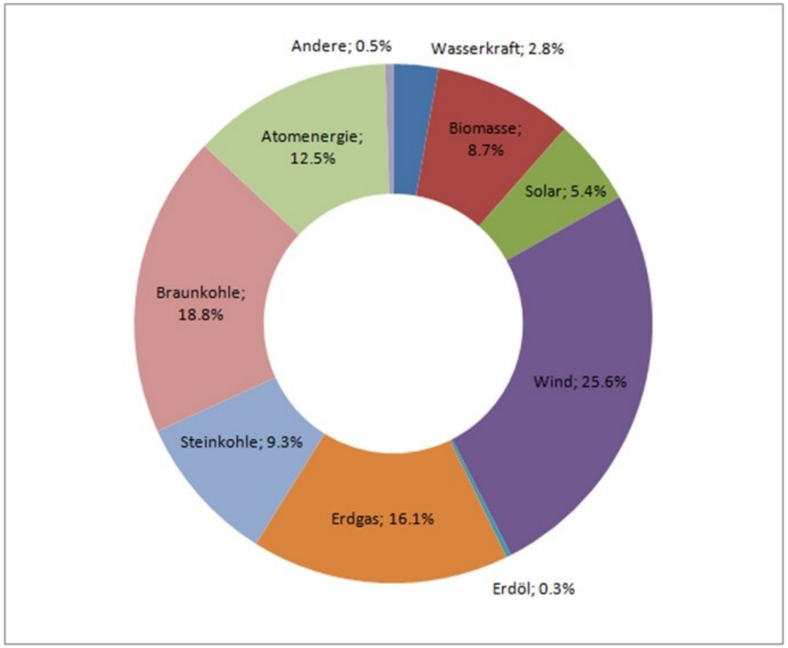
Right:
Fuel consumption of a modern aircraft (Airbus A320).
For the Bathtub Curve see also above under "Aircraft Fuel Consumption"

In Short: Aircraft – Train

The aircraft is on short-haul not efficient. Choose the train!

electricity mix in Germany (I/2021)

42.5% renewable energy



Fraunhofer 2021

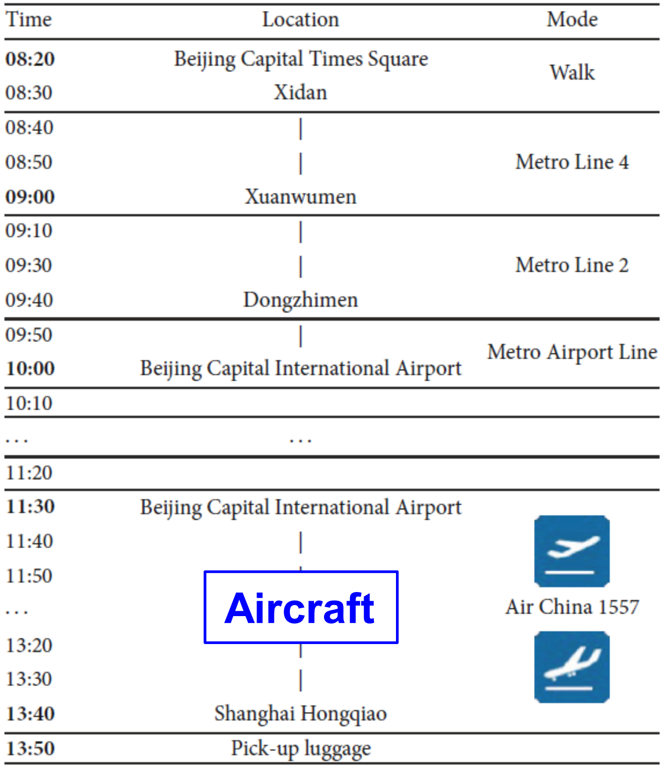
- **The train is about 3 times better in energy efficiency** (for sure on short range)
- **The train is using up to 50% renewable electricity (Factor 2)**
- **Aircraft Factor 3*, because of additional non-CO2-effects of:**
  - ○ **NOx**
  - ○ **AIC**
- **3*2*3: The aircraft causes 18-fold global warming!**

* Also possible: Factor 2 because of lower cruise altitude. That would result in 3*2*2 = 12 for the final result.

Medium Range

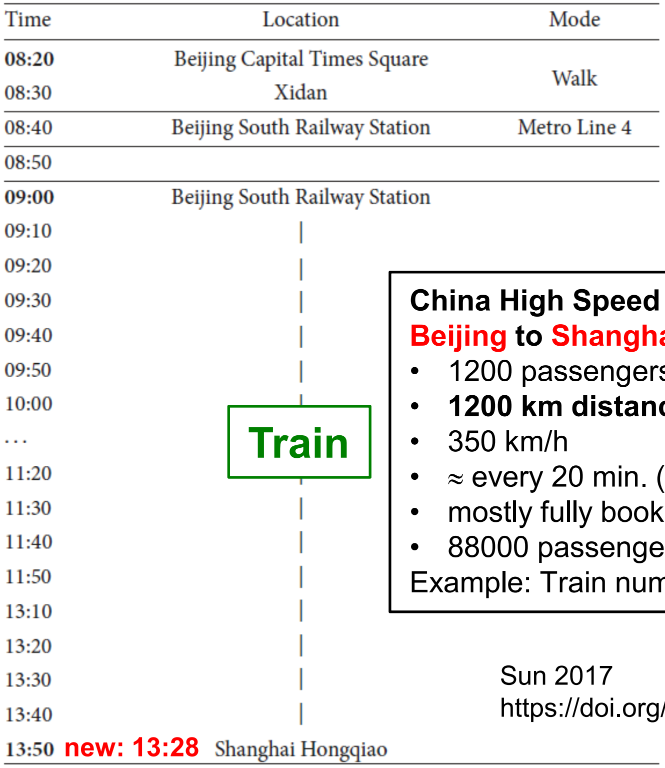
Medium Range between Megacities the Train is Better!

Connection of neighboring megacities – Beijing & Shanghai – Comparison Aircraft and Train



Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40	|	Metro Line 4
08:50	|	
09:00	Xuanwumen	
09:10	|	Metro Line 2
09:30	|	
09:40	Dongzhimen	
09:50	|	Metro Airport Line
10:00	Beijing Capital International Airport	
10:10		
. . .	. . .	
11:20		
11:30	Beijing Capital International Airport	✈ Air China 1557 ✈
11:40	|	
11:50	|	
. . .	**Aircraft**	
13:20	|	
13:30	|	
13:40	Shanghai Hongqiao	
13:50	Pick-up luggage	

(a) Travel mode: metro + aircraft



Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40	Beijing South Railway Station	Metro Line 4
08:50		
09:00	Beijing South Railway Station	
09:10	|	
09:20	|	
09:30	|	
09:40	|	
09:50	|	
10:00		
. . .	**Train**	
11:20		
11:30	|	
11:40	|	
11:50	|	
13:10	|	
13:20	|	
13:30	|	
13:40	|	
13:50 **new: 13:28**	Shanghai Hongqiao	

(b) Travel mode: metro + high-speed rail

China High Speed Rail (CHR)
Beijing to Shanghai:
- 1200 passengers per train
- **1200 km distance**
- 350 km/h
- ≈ every 20 min. (one A380 every 10 min.)
- mostly fully booked
- 88000 passengers per day (both directions)

Example: Train number G1

Sun 2017
https://doi.org/10.1155/2017/8426926

- Comparison **Air Transport versus High-Speed Rail**
for a trip from Beijing Capital Times Square to Shanghai Hongqiao in China.
- Despite the large distance of more than 1200 km,
Passengers arrive about **the same time**. Probability of delays is much less in the train.

Summary (1 of 2)

- The 1.5 °C threshold was passed in 2023.
- The 2.0 °C threshold will probably be passed in 2042.
- 1% of the world's population are responsible for 50% of commercial avaition emissions.
- What matters? 1.) water, 2.) global warming, 3.) energy – in this sequence.
- Life Cycle Assessment (LCA) in Aviation: 99.9% from operation.
- Climate Change is with 68% the most important midpoint contribution to the LCA single score.
- For aviation LCA is missing altitude effects and noise (but was added).
- A simple method exist for altitude-dependent equivalent CO2 mass calculation.
- Improvement: Contrails in equivalent CO2 mass calculation are considered not only by length, but also by fuel consumption.
- Equivalent CO2 mass calculation yields 50% due to AIC at 36000 ft.
- Aircraft fuel consumption versus range follows a "bathtub curve".
- NOx has major influence on local air pollution at airports.
- The Ecolabel for Aircraft is the simplified version of the LCA.
- Battery electric flight does not allow required range.
- E-fuels (SAF) need far more renewable energy than available.
- Renewable energy is best used to substitue coal power plants (not for e-fuels, not for LH2).
- The e-fuel carbon cycle must use CO2 from the air (not from a point source).

Summary (2 of 2)

- Goal setting by the aviation industry failed and will continue to fail.
- The battle against greenwashing intensifies.
- Contrails can be predicted by physics (Schmidt-Appleman Criterion and Diagram).
- Most warming contrails are those at dusk, dawn, and at night.
- Contrails.org offers a tool that can be used for contrail avoidance in flight planning for free.
- Strategic contrail avoidance is done by incorporating it into the flight plan - invisible to controllers.
- SATAVIA (DECISIONX:NETZERO) and FlightKeys (5D) are the two companies, who offer contrail avoidance tools as of today (2024-06-10).
- Earth-bound modes of transport show less drag due to lift or weight.
- Any thruster in air (propeller, jet) has less efficiency than a wheel.
- Coparisons in electro mobility must not be done on the basis of energy, but on the basis of equivalent CO2.
- The Karman-Gabrielli Diagram offers much inside when comparing modes of transport: "What price speed?"
- A modern car is better, even with only one person traveling, than an aircraft, if equivalent CO2 are compared.
- An aircraft is by a factor 12 to 18 worse on short range with respect to equivalent CO2.
- High speed trains can compete even on distances of 1200 km with aircraft, if operating between megacities (Beijing & Shanghai).

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http://www.ProfScholz.de
http://AERO.ProfScholz.de

How to quote this document:

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