Supplementary information of

Using aviation fuel hydrogen content to assess contrails and climate impact

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Supplementary Table 1 | Composition of probed fuels. The carbon content is manually derived based on FHC and the H/C ratio.

Campaign	Fuel composition	Hydrogen content [%m/m]	Carbon content [%m/m]	Sulfur content [%m/m]	Aromatic content [%v/v]	Naphthalene content [%v/v]
ELIF1-2/ NDMAX[4]	**Jet A-1**	**13.73**	**86.11**	**0.135**	**17.2**	**1.83**
	59% Jet A-1 + 41% FT-SPK	**14.36**	**85.55**	**0.057**	**11.4**	**0.82**
	59% Jet A-1(Ref2) + 41% HEFA-SPK	**14.40**	**85.79**	**0.007**	**8.5**	**0.61**
	70% Jet A-1(Ref3) + 30% HEFA-SPK	**14.51**	**85.59**	**<0.001**	**9.5**	**0.05**
ECLIF3-1[22]	**Jet A-1**	**14.08**	**85.90**	**0.0211**	**13.4**	**0.35**
	100% HEFA-SPK	**15.11**	**84.89**	**0.0007**	**NA**	**<0.08**
ECLIF3-2[32]	**Jet A-1**	**14.25**	**85.74**	**0.0125**	**13.4**	**0.50**
	100% HEFA-SPK	**15.18**	**84.82**	**0.0003**	**<0.1**	**<0.08**
	62% Jet A-1 + 38% HEFA-SPK	**14.39**	**85.56**	**0.0505**	**10.8**	**0.58**
NEOFUELS/ VOLCAN1[48]	**Jet A-1**	**14.20**	**85.80**	**0.138**	**13.1**	**0.4**
	100% HEFA-SPK	**15.30**	**84.70**	**0.0006 (0.0003)**	**<1**	**<0.1**
NEOFUELS/ VOLCAN2[5,48]	**Jet A-1**	**14.10**	**85.90**	**0.0195**	**12.8**	**0.60**
	19% Jet A-1 + 81% HEFA-SPK	**15.10**	**84.90**	**0.0041**	**2.5**	**0.20**
	HEFA-SPK + low aromatics	**14.80**	**85.20**	**0.0009 (0.0002)**	**8.4**	**<0.1**
	HEFA-SPK + high aromatics	**14.30**	**85.70**	**<0.0004 (0.0001)**	**17.6**	**<0.1**

Supplementary Table 2 | Fleet-aggregated statistics for nvPM emissions, contrail properties and radiative effects as a function of fuel hydrogen content (FHC) over Europe and adjacent North Atlantic, simulated for every 6th day of 2019. The data compare simulations with increasing FHC against conventional kerosene, taking the Ref at 13.8% FHC.

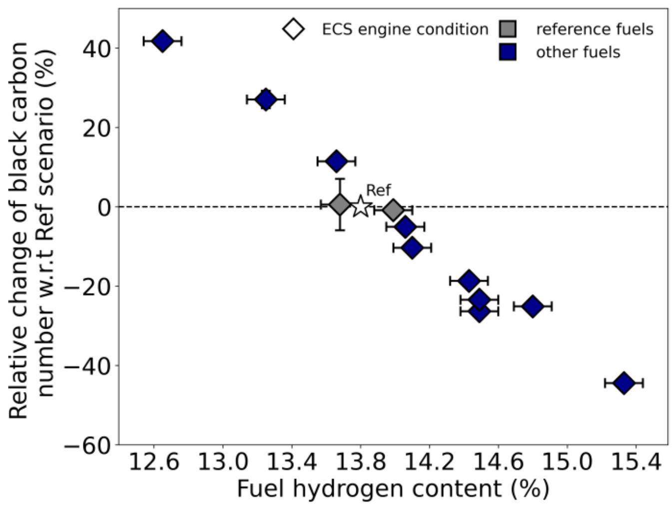
Fleet-aggregated emissions and contrail properties	Baseline (13.8% FHC)	14.0% FHC	14.2% FHC	14.4% FHC	14.6% FHC	14.8% FHC	15.0% FHC	15.2% FHC	15.4% FHC	% change: 15.2% FHC vs Ref
Mean EI_{nv} ($\times 10^{15}$ kg^{-1})	**1.22**	**1.04**	**0.872**	**0.73**	**0.635**	**0.559**	**0.503**	**0.47**	**0.45**	**-61%**
Mean N_{ice} per contrail length ($\times 10^{12}$ m^{-1})	**3.12**	**2.65**	**2.20**	**1.84**	**1.59**	**1.41**	**1.27**	**1.18**	**1.12**	**-62%**
Potential contrail formation (%)	**13.37**	**13.40**	**13.49**	**13.62**	**13.79**	**13.97**	**14.12**	**14.2**	**14.32**	**+6%**
Mean contrail age (h)	**2.37**	**2.31**	**2.22**	**2.13**	**2.05**	**1.99**	**1.94**	**1.90**	**1.87**	**-20%**
Segment contrail optical depth	**0.124**	**0.118**	**0.112**	**0.106**	**0.102**	**0.098**	**0.096**	**0.094**	**0.092**	**-24%**
Contrail cirrus cover (%)	**0.67**	**0.63**	**0.59**	**0.54**	**0.51**	**0.48**	**0.46**	**0.44**	**0.43**	**-34%**
Mean $EF_{contrails}$ ($\times 10^{11}$ J)	**2.19**	**1.95**	**1.66**	**1.46**	**1.31**	**1.22**	**1.13**	**1.05**	**1.01**	**-52%**

For fleet-averaged nvPM emissions indices EI_{nv}, our Ref simulations yield 1.22×10^{15} kg^{-1}, similar to the European mean of 1.16×10^{15} kg^{-1} provided by Teoh et al.[20]. The slightly higher EI_{nv} is likely due to the mapping of lean-burn engines, whose volatile particle emissions are not well parameterized, to RQL counterparts. The estimated potential contrail formation over Europe is 13.37%, slightly lower than the 16.21% over the North Atlantic in Teoh et al.[52]. This difference can be attributed to the warmer upper-tropospheric temperatures and less ice supersaturated regions over Europe. The simulated mean contrail age (2.37 h) falls within their reported scale, centered around 1.9 h, with differences probably due to meteorological variability and RHi corrections. The age distribution ranges from 0.6 to 3.5 hours (25th–75th). The contrail optical depth over Europe in the Ref simulations (0.124) is similar to the global average of 0.14 reported by Teoh et al.[20]. The simulated contrail cirrus cover over Europe is 0.67%, comparable to 0.95% for Europe by Teoh et al.[20]. The global-scale simulation allows contrails formed outside Europe to be advected into the region that may increase coverage, in contrast to the Europe-focused simulations considered here.

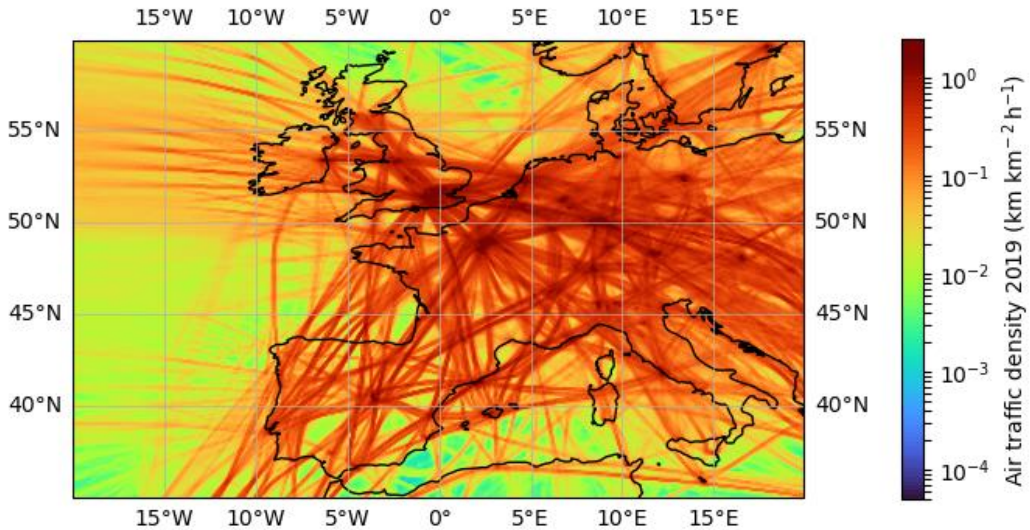
Supplementary Table 3 | Fleet-aggregated statistics of impact of changes in soot number on nvPM emissions, contrail properties, and radiative effects as a function of fuel hydrogen content (FHC) over Europe and adjacent North Atlantic, simulated for every 6th day of 2019. The data compare simulations with increasing FHC and ±20% soot number against the corresponding FHC.

Fleet-aggregated emissions and contrail properties	Baseline (13.8%, no high or low soot)	+ / - 20% soot number scenario					(%) change: 15.2% FHC vs Ref for high or low soot
		13.8% FHC	14.2% FHC	14.6% FHC	15.0% FHC	15.4% FHC	
Mean EI_{nv} ($\times 10^{15}$ kg^{-1})	**1.22**	**1.46/0.97**	**1.05/0.70**	**0.76/0.51**	**0.60/0.40**	**0.54/0.36**	**±20% / [+20%, -19%]**
Mean N_{ice} per contrail length ($\times 10^{12}$ m^{-1})	**3.12**	**3.72/2.49**	**2.65/1.77**	**1.92/1.28**	**1.49/1.02**	**1.34/0.89**	**[+19%, -20%] / ±19%**
Mean contrail age (h)	**2.37**	**2.45/2.28**	**2.29/2.11**	**2.13/1.95**	**1.99/1.84**	**1.94/1.77**	**[+3%, -4%] / [+3%, -5%]**
Segment contrail optical depth	**0.12**	**0.13/0.12**	**0.12/0.10**	**0.11/0.10**	**0.10/0.09**	**0.10/0.09**	**[+6%, -7%] / ±6%**
Contrail cirrus cover (%)	**0.67**	**0.72/0.62**	**0.64/0.54**	**0.55/0.47**	**0.48/0.42**	**0.46/0.39**	**[+8%, -7%] / ±8%**
Mean $EF_{contrails}$ ($\times 10^{11}$ J)	**2.19**	**2.40/1.88**	**1.95/1.46**	**1.53/1.14**	**1.32/0.95**	**1.16/0.86**	**[+10%, -14%] / [+17%, -15%]**

The EI_{nv} deviations from the reference scenario (with high- or low-soot numbers) are ±20% at 13.8% FHC and [+20%, -19%] at 15.2% FHC, reflecting the prescribed soot variations at FHC levels. Changes in initial N_{ice} from the high- and low-soot scenarios, compared to the reference, fall within [+19%, -20%] for 13.8% FHC and within ±19% for 15.2% FHC. For the contrail lifecycle and radiative variables, contrail age varies by [+3%, –4%] at 13.8% FHC and [+3%, –5%] at 15.2% FHC; contrail optical depth changes by [+6%, –7%] and ±6%, while cirrus coverage by [+8%, –7%] and ±8%. The resulting EF variation ranges by [+10%, -14%] at 13.8% FHC, and within [+17%, –15%] at 15.2% FHC, relative to reference.



Supplementary Fig. 1 | Ground-engine measurements linking fuel hydrogen content to black carbon number emissions. Ground-engine measurements from the JETSCREEN project[79] and the ECLIF campaign, obtained under controlled Environmental Control System (ECS) engine operating conditions, show the dependence of normalized black carbon number on fuel hydrogen content. Relative changes are referenced to the normalized black carbon number at a reference FHC of 13.8%, obtained by linear interpolation between neighboring measurements. Horizontal error bars represent a fuel hydrogen content uncertainty of ±0.11%, and vertical error bars denote the standard deviation of measurements. Grey symbols indicate the reference Jet A-1 fuels, and dark blue symbols represent the remaining fuels. This ground-based relationship provides the experimental basis for the study and is subsequently evaluated using independent in-flight observations of nvPM number emissions and contrail ice particle numbers.



Supplementary Fig. 2 | Air traffic density. A total of 1,578,734 flights over Europe and adjacent North Atlantic every 6th day in 2019 is simulated within the scope of this study. The calculation method is based on Teoh et al.[20].