Last updated: November 1, 2026

🗺️ Four-year roadmap · Year 4, Spring · 🧮 Built-in calculator

About this course

This free course has 10 units and 6 labs. Those are the real counts, not a longer syllabus cut short.

A check is one number or code result on a course page that a script recomputes before the page is published. The printed number and the recomputed number have to match.

> This is a free self-study course outline written by Saving Planets. It is not a university course, it carries no academic credit, and no school is involved.
>
> Its scope follows a senior elective on aviation and the environment. It draws on the environmental-factors lecture in MIT 16.885J Aircraft Systems Engineering (free on MIT OpenCourseWare) and on public NASA, DOE, EIA and EPA material, which we link where it helps. None of them endorses this page.
>
> What we add: every unit ties to real work with a cited public source, every number on the page is re-computed by a checking script before it goes live, and every lab runs in a free spreadsheet or simulation.
>
> Work through it in order. Each unit has goals, key ideas, equations, step-by-step examples, practice with full answers, common mistakes, flashcards and a quiz. Your progress is saved only in this browser.

How this course helps save the planet

This whole course is a planet section: DOE's Alternative Fuels Data Center says aviation produces about 2% of all CO_2 worldwide and 12% of CO_2 from transportation, and contrails add warming beyond CO_2.

NASA's Sustainable Flight National Partnership works toward the aviation community's goal of net-zero carbon emissions by 2050. Each unit ends with a short, sourced section. Values that are not from a source are labeled as sample or textbook values.

For instructors

You can teach this course, or let a student work through it alone. It is free. Saving Planets does not give a grade or school credit.

- This page is the whole course: 10 units and 6 labs (AERO 470).
- Plan on 15 weeks, about 6 to 9 hours a week, including the lab weeks.
- Follow the 15-week schedule. Read the unit, do the practice on paper, then open the answer. In a lab week, do the lab or the home version.
- A check is one number or code result on the page that a script recomputes before we publish. The number you see and the recomputed number have to match.
- Use Print this page, or download the PDF study guide. The formula sheet is near the end.
- Ask: how does this unit help people and the planet? Each unit has a green box with a sourced fact.
- Copy the teacher guide template and write in your class name, the time you have, and the questions you will ask. Open the teacher guide template

Before you start

Prerequisites

- Propulsion: thrust, efficiency and TSFC.
- Aircraft Performance: lift, drag and the Breguet range equation.
- Thermodynamics: energy, heating values and cycle efficiency.
- Capstone Design or Avionics & Systems Engineering: requirements and trades.

How to study

- Keep units straight: kg, gallons, liters, MJ and Wh.
- Always ask “per what?”: per flight, per passenger-km, per kg of fuel.
- Separate combustion CO_2 from lifecycle CO_2.
- Check every claimed saving against a baseline.
- Remember non-CO_2 effects such as contrails.
- Do every practice problem on paper before opening the answer, and retake the quizzes a few days later.

What you need

- Spreadsheet software (any free one works), or Python.
- A computer or tablet for the free PhET Greenhouse Effect simulation.
- The free MIT 16.885J lecture notes in a web browser.
- A calculator.

Suggested 15-week schedule

About 6 to 9 hours a week: reading, practice problems and, in lab weeks, the lab.

Week	Unit	Topics	Reading
1	Aviation and Climate: Counting CO_2	Counting CO_2; Lab A	EIA
2	Efficiency Metrics	Efficiency metrics	NASA SFNP
3	Aerodynamic Efficiency	L/D and induced drag	MIT 16.885J
4	Aerodynamic Efficiency	Breguet fuel burn; Lab B	NASA SFNP
5	Engine Efficiency	Engine efficiency; Lab C	MIT 16.885J
6	Sustainable Aviation Fuels	SAF basics	DOE AFDC
7	Sustainable Aviation Fuels	SAF lifecycle; Lab D; midterm practice	DOE AFDC
8	Contrails and Non-CO_2 Effects	Contrails	NASA-DLR
9	Electric and Hybrid Propulsion	Batteries and electric range	NASA SFNP
10	Electric and Hybrid Propulsion	Hybrid systems; Lab E	NASA SFNP
11	Hydrogen Aircraft	Hydrogen aircraft	MIT 16.885J
12	Operations, Noise and Air Quality	Operations	NASA SFNP
13	Operations, Noise and Air Quality	Noise and air quality	EPA
14	Pathways to Net Zero	Scenarios; Lab F	DOE AFDC
15	Pathways to Net Zero	Review; final practice	MIT 16.885J

Your progress

Tick units and labs as you finish them, and take the quizzes. Progress and quiz scores are saved only in this browser, never sent to us.

Units

Aviation and Climate: Counting CO_2

Where aviation emissions come from, emission factors, combustion versus lifecycle CO_2, and aviation's share of the total.

Learning objectives

By the end of this unit you can:

- Use an emission factor to compute CO_2.
- Convert between gallons, liters and kilograms.
- Explain combustion versus lifecycle CO_2.
- State aviation's share of global CO_2.

Key concepts

- Burning jet fuel turns its carbon into CO_2; the mass of CO_2 is about three times the fuel mass because each carbon atom gains two oxygen atoms.
- The U.S. EIA gives 21.50 lb (9.75 kg) of CO_2 per gallon of jet fuel burned.
- Lifecycle CO_2 adds production and transport of the fuel; for sustainable fuels, growing the feedstock can absorb CO_2.
- DOE's Alternative Fuels Data Center says aviation accounts for 2% of all CO_2 and 12% of transportation CO_2 worldwide.
- Aviation also warms the climate through non-CO_2 effects such as contrails and NOx.

Key equations

$$m_{CO_2} = EF \times V_{fuel}$$

`m_CO_2=EF× V_fuel`

Emissions from fuel volume

$$EF = 9.75\ \mathrm{kg/gal}$$

`EF=9.75\ kg/gal`

EIA jet fuel factor

$$1\ \mathrm{gal} = 3.785\ \mathrm{L}$$

`1\ gal=3.785\ L`

Volume conversion

$$\frac{44}{12} \approx 3.67$$

CO_2-to-carbon mass ratio

Worked examples, step by step

Example 1.1 A flight burns 5000 gallons of jet fuel. CO_2?

1. 5000 × 9.75.

Answer: 48,750 kg (48.75 t).

Example 1.2 Check EIA's pound and kilogram values.

1. 21.50 × 0.45359237.

Answer: 9.75 kg, consistent.

Example 1.3 How many liters is 5000 gallons?

1. 5000 × 3.785.

Answer: 18,927 L.

Practice problems

Work each on paper first, then check.

1. CO_2 from 1000 gallons?

   9750 kg.

2. Mass ratio of CO_2 to carbon?

   44/12 = 3.67.

3. Aviation's share of transport CO_2 (DOE)?

   12%.

4. What does lifecycle add?

Production, transport and feedstock effects.

Common misconceptions

Myth: CO_2 weighs less than the fuel.

Actually: It weighs about three times more.

Myth: Aviation only emits CO_2.

Actually: Contrails and NOx matter too.

Myth: Lifecycle and combustion CO_2 are equal.

Actually: They differ, especially for SAF.

Flashcards

Emission factor

CO_2 per unit fuel.

Combustion CO_2

From burning.

Lifecycle CO_2

Well-to-wake total.

Non-CO_2 effects

Contrails, NOx, soot.

Jet A

Standard jet fuel.

t CO_2

Tonne of CO_2.

Self-check quiz

1. CO_2 from 5000 gal...

48,750 kg

4875 kg

9750 kg

487,500 kg

48,750 kg. × 9.75.

2. EIA factor...

9.75 kg/gal

3.16 kg/gal

21.5 kg/gal

1 kg/gal

9.75 kg/gal. EIA.

3. Aviation share of all CO_2...

2%

12%

25%

0.2%

2%. DOE.

4. Liters in 5000 gal...

18,927

1321

5000

37,854

18,927. × 3.785.

Try this quiz again

How this helps save the planet

The U.S. EIA lists 21.50 lb (9.75 kg) of CO_2 per gallon of jet fuel.

DOE's Alternative Fuels Data Center says aviation accounts for 2% of all CO_2 worldwide and 12% of all CO_2 from transportation.

On Saving Planets: Solutions · Earth Observation

Sources: U.S. EIA: Carbon dioxide emissions coefficients (https://www.eia.gov/environment/emissions/co2_vol_mass.php) · U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel)

Free learning resources

- U.S. EIA: Carbon dioxide emissions coefficients (https://www.eia.gov/environment/emissions/co2_vol_mass.php): EIA table.
- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.

☐ **I finished this unit**

Efficiency Metrics

Fuel and CO_2 per passenger-kilometer, energy intensity, and how to compare aircraft fairly.

Learning objectives

By the end of this unit you can:

- Compute fuel per passenger-km.
- Compute CO_2 per passenger-km.
- Apply a percentage efficiency gain.
- Compare fairly across aircraft.

Key concepts

- Total emissions mislead; normalize by passengers and distance.
- Load factor matters: empty seats raise emissions per passenger.
- Energy intensity (MJ per passenger-km) compares different fuels on one scale.
- An efficiency gain lowers fuel per unit of transport, not necessarily total fuel if traffic grows.
- NASA's Sustainable Flight National Partnership targets 25–30% energy-efficiency improvements in next-generation transports.

Key equations

$$\frac{V_{fuel}}{n_{pax} d}$$

Fuel per passenger-km

$$\frac{m_{CO_2}}{n_{pax} d}$$

CO_2 per passenger-km

$$m' = m(1 - g)$$

`m^=m(1-g)`

After a fractional gain g

$$LF = \frac{n_{pax}}{n_{seats}}$$

`LF=_paxn_seats`

Load factor

Worked examples, step by step

Example 2.1 5000 gallons carry 180 passengers 2000 km (sample values). Liters per passenger-km?

1. 18,927/(180 × 2000).

Answer: 0.0526 L.

Example 2.2 CO_2 per passenger-km?

1. 48,750/360,000.

Answer: 0.135 kg (135 g).

Example 2.3 A 25% efficiency gain on the same trip. New CO_2?

1. 48,750 × 0.75.

Answer: 36,563 kg.

Practice problems

Work each on paper first, then check.

1. Same flight with 150 passengers: g CO_2 per pkm?

   162.5 g.

2. Load factor, 180 of 200 seats?

   0.9.

3. A 30% gain on 48,750 kg?

   34,125 kg.

4. Why normalize?

   To compare different trips and aircraft fairly.

Common misconceptions

Myth: Bigger planes always emit more per passenger.

Actually: Often less per passenger.

Myth: Efficiency cuts total emissions.

Actually: Only if traffic doesn't grow faster.

Myth: Seats equal passengers.

Actually: Use load factor.

Flashcards

Passenger-km

One passenger carried one km.

Load factor

Passengers over seats.

Energy intensity

MJ per pkm.

Rebound

Growth offsetting efficiency.

Baseline

Reference case.

Normalization

Per-unit comparison.

Self-check quiz

1. L per pkm...

0.0526

0.526

5.26

0.00526

0.0526. 18,927/360,000.

2. g CO_2 per pkm...

135

13.5

1350

48.75

135. 48,750/360,000.

3. After 25% gain...

36,563 kg

12,188 kg

48,750 kg

60,938 kg

36,563 kg. × 0.75.

4. SFNP target...

25–30%

2–3%

50–70%

100%

25–30%. NASA.

Try this quiz again

How this helps save the planet

NASA says the Sustainable Flight National Partnership aims to enable 25–30% energy-efficiency improvements in next-generation transports that can use 100% sustainable aviation fuel and fly optimal trajectories.

This unit's per-passenger metrics are how such gains are measured.

On Saving Planets: Aircraft Performance · Solutions

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.
- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.

☐ **I finished this unit**

Aerodynamic Efficiency

L/D, induced drag and aspect ratio, high-aspect-ratio and truss-braced wings, and fuel burn from the Breguet equation.

Learning objectives

By the end of this unit you can:

- Compute fuel fraction from Breguet.
- Show how L/D cuts fuel.
- Compute induced drag coefficient.
- Explain why long, slender wings save fuel.

Key concepts

- From Breguet, the fuel fraction is 1 − exp(−Rc/(V·L/D)).
- Higher L/D means less fuel for the same range.
- Induced drag C_Di = C_L²/(πeAR) falls as aspect ratio rises.
- Very slender wings need bracing (truss-braced designs) to stay light and stiff.
- NASA's partnership centerpiece is a full-scale X-plane demonstrator testing an ultra-efficient aerodynamic design.

Key equations

$$\frac{W_f}{W_i} = 1 - e^{-Rc/(V\,L/D)}$$

`(W_f)/(W_i)=1-e^-Rc/(V L/D)`

Fuel fraction

$$C_{D_i} = \frac{C_L^2}{\pi e AR}$$

`C_D_i=(C_L^2)/(π eAR)`

Induced drag

$$AR = b^2/S$$

`AR=b^2/S`

Aspect ratio

$$L/D = C_L/C_D$$

`L/D=C_L/C_D`

Lift-to-drag ratio

Worked examples, step by step

Example 3.1 3000 km at 230 m/s, c = 0.6 /h, L/D = 17 (textbook values). Fuel fraction?

1. Rc/(V L/D) = 3 × 10^6 × 1.667 × 10^{-4}/(230 × 17) = 0.1279.
2. 1 − e^(−0.1279).

Answer: 0.120.

Example 3.2 Same with L/D = 20.

1. 1 − e^(−0.1087).

Answer: 0.103: 14.2% less fuel.

Example 3.3 C_Di at C_L = 0.5, e = 0.85, AR = 9?

1. 0.25/(π × 0.85 × 9).

Answer: 0.0104.

Practice problems

Work each on paper first, then check.

1. C_Di at AR = 12?

   0.0078.

2. At AR = 19 (truss-braced class)?

   0.0049.

3. Aspect ratio for b = 36 m, S = 120 m^2?

   10.8.

4. Why brace a slender wing?

   To keep it light and stiff.

Common misconceptions

Myth: Drag is all friction.

Actually: Induced drag is large at cruise.

Myth: Longer wings are free.

Actually: Weight and gate limits.

Myth: Fuel scales linearly with L/D.

Actually: It follows the exponential.

Flashcards

L/D

Lift-to-drag ratio.

Induced drag

Drag due to lift.

Aspect ratio

b^2/S.

Oswald factor

Span efficiency e.

Truss-braced wing

Slender wing with struts.

Fuel fraction

Fuel over takeoff weight.

Self-check quiz

1. Fuel fraction, L/D 17...

0.120

0.103

0.128

0.017

0.120. Breguet.

2. Fuel saved at L/D 20...

14.2%

17.6%

3%

30%

14.2%. Compare fractions.

3. C_Di AR 9...

0.0104

0.104

0.00104

0.0078

0.0104. $C_L^2/(\pi eAR)$.

4. Higher AR...

lowers induced drag

raises it

no effect

raises friction only

lowers induced drag. Formula.

Try this quiz again

How this helps save the planet

NASA says the centerpiece of its Sustainable Flight National Partnership will be a full-scale X-plane demonstrator built to test an ultra-efficient aerodynamic design, to inform the next generation of single-aisle aircraft.

NASA lists the demonstrator's first flight as no earlier than late 2026.

On Saving Planets: Aerodynamics I · Aircraft Performance

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.
- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.

☐ **I finished this unit**

Engine Efficiency

Thermal, propulsive and overall efficiency, bypass ratio, and advanced engine cores.

Learning objectives

By the end of this unit you can:

- Compute propulsive efficiency.
- Combine thermal and propulsive efficiency.
- Explain why high bypass saves fuel.
- Relate efficiency to TSFC.

Key concepts

- Overall efficiency is thermal efficiency times propulsive efficiency.
- Propulsive efficiency 2/(1 + V_e/V_0) rises as exhaust velocity approaches flight speed.
- High-bypass turbofans move more air more slowly, raising propulsive efficiency.
- Hotter, higher-pressure, compact cores raise thermal efficiency.
- NASA's Hybrid Thermally Efficient Core work develops high-power-density turbine cores for next-generation transports.

Key equations

$$\eta_p = \frac{2}{1 + V_e/V_0}$$

`_p=(2)/(1+V_e/V_0)`

Propulsive efficiency

$$\eta_o = \eta_{th}\eta_p$$

`_o=_th_p`

Overall efficiency

$$TSFC \propto \frac{V_0}{\eta_o}$$

Fuel use per thrust

$$BPR = \dot{m}_{bypass}/\dot{m}_{core}$$

`BPR= m_bypass/ m_core`

Bypass ratio

Worked examples, step by step

Example 4.1 V_0 = 230 m/s, V_e = 400 m/s. η_p?

1. 2/(1 + 400/230).

Answer: 0.730.

Example 4.2 Lower V_e to 300 m/s (higher bypass).

1. 2/(1 + 300/230).

Answer: 0.868.

Example 4.3 With η_th = 0.5, overall efficiency at V_e = 300?

1. 0.5 × 0.868.

Answer: 0.434.

Practice problems

Work each on paper first, then check.

1. η_p at V_e = 350 m/s?

   0.793.

2. Overall at V_e = 400, η_th = 0.5?

   0.365.

3. Fuel saving from 0.365 to 0.434 overall?

   15.9% less fuel for the same work.

4. What is bypass ratio?

   Bypass over core mass flow.

Common misconceptions

Myth: Faster exhaust is more efficient.

Actually: It lowers propulsive efficiency.

Myth: Thermal efficiency is everything.

Actually: Propulsive matters as much.

Myth: Bypass is free.

Actually: Bigger fans add weight and drag.

Flashcards

Propulsive efficiency

Useful thrust power fraction.

Thermal efficiency

Cycle efficiency.

Overall efficiency

Product of both.

Bypass ratio

Fan air over core air.

TSFC

Fuel per thrust per time.

Engine core

Compressor, burner, turbine.

Self-check quiz

1. η_p at 400...

0.730

0.868

0.575

1.0

0.730. 2/(1 + 1.739).

2. η_p at 300...

0.868

0.730

0.5

0.95

0.868. 2/(1 + 1.304).

3. Overall...

0.434

0.868

0.5

0.25

0.434. 0.5 × 0.868.

4. High bypass...

raises η_p

lowers η_p

raises V_e

no effect

raises η_p. Slower jet.

Try this quiz again

How this helps save the planet

NASA says its Hybrid Thermally Efficient Core work is accelerating the development and demonstration of advanced turbine engine technologies in a high-power-density core for next-generation commercial transports.

Both efficiencies in this unit feed directly into the fuel burned per passenger.

On Saving Planets: Propulsion · Thermodynamics

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.
- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.

☐ **I finished this unit**

Sustainable Aviation Fuels

What SAF is, production pathways, blend limits, lifecycle reductions and national goals.

Learning objectives

By the end of this unit you can:

- Define SAF.
- Compute blended lifecycle savings.
- Size goal-level savings.
- Explain blend limits.

Key concepts

- DOE defines SAF as an alternative fuel made from non-petroleum feedstocks that reduces air pollution from air transportation.
- SAF can be blended at levels between 10% and 50%, depending on feedstock and production pathway (ASTM D7566).
- Blended SAF works in existing aircraft and infrastructure.
- Lifecycle savings scale with blend fraction times the SAF's own lifecycle reduction.
- The SAF Grand Challenge aims for 3 billion gallons in 2030 and 35 billion in 2050 with at least 50% lifecycle reduction.

Key equations

$$s = b \times r$$

`s=b× r`

Blend saving = blend × SAF reduction

$$m_{saved} = V \times EF \times r$$

`m_saved=V× EF× r`

CO_2 saved by SAF volume

$$b \leq 0.5$$

Maximum blend (pathway-dependent)

$$EF = 9.75\ \mathrm{kg/gal}$$

$EF = 9.75\ \text{kg/gal}$

EIA factor

Worked examples, step by step

Example 5.1 A 50% blend of SAF with a 50% lifecycle reduction. Overall saving?

1. 0.5 × 0.5.

Answer: 25%.

Example 5.2 3 billion gallons with a 50% reduction, using the EIA factor as the baseline (simplified).

1. $3 \times 10^9 \times 9.75 \times 0.5$.

Answer: About 14.6 million tonnes CO_2 a year.

Example 5.3 Same for 35 billion gallons.

1. $35 \times 10^9 \times 9.75 \times 0.5$.

Answer: About 171 million tonnes.

Practice problems

Work each on paper first, then check.

1. A 10% blend at 80% reduction?

   8%.

2. Flights using SAF per ICAO via DOE?

   Over 360,000 at 46 airports.

3. Why the blend limit?

   Fuel properties must meet Jet A specifications.

4. Does SAF need new engines?

   Blends work in existing aircraft.

Common misconceptions

Myth: SAF has zero emissions.

Actually: It burns to CO_2; savings are lifecycle.

Myth: Any blend works.

Actually: Limits depend on pathway.

Myth: SAF only affects CO_2.

Actually: NASA-DLR found fewer contrail ice crystals.

Flashcards

SAF

Sustainable aviation fuel.

HEFA

Hydroprocessed esters and fatty acids pathway.

Blend limit

Maximum SAF share.

ASTM D7566

Synthetic jet fuel spec.

Lifecycle reduction

Cut vs fossil fuel.

Drop-in fuel

Works in existing systems.

Self-check quiz

1. Blend saving...

25%

50%

100%

75%

25%. 0.5 × 0.5.

2. 2030 savings...

≈ 14.6 Mt

≈ 1.5 Mt

≈ 146 Mt

≈ 29 Mt

≈ 14.6 Mt. × 9.75 × 0.5.

3. Blend range...

10–50%

0–5%

90–100%

unlimited

10–50%. DOE.

4. 2050 goal...

35 billion gal

3 billion gal

360,000 gal

46 billion gal

35 billion gal. DOE.

Try this quiz again

How this helps save the planet

DOE's Alternative Fuels Data Center says over 360,000 commercial flights have used SAF at 46 airports (per ICAO), and the SAF Grand Challenge aims for 3 billion gallons in 2030 and 35 billion

gallons in 2050 with at least 50% lifecycle reduction.

DOE notes that all three existing U.S. plants use the HEFA pathway, with alcohol-to-jet plants expected.

On Saving Planets: Solutions · General Chemistry I

Sources: U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel)

Free learning resources

- U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel): DOE SAF page.
- U.S. EIA: Carbon dioxide emissions coefficients (https://www.eia.gov/environment/emissions/co2_vol_mass.php): EIA factors.

☐ **I finished this unit**

Contrails and Non-CO_2 Effects

How contrails form, why they warm, soot and ice crystals, and how fuels and routing reduce them.

Learning objectives

By the end of this unit you can:

- Explain contrail formation.
- Compute ice-crystal reductions.
- Describe non-CO_2 warming.
- Name mitigation options.

Key concepts

- Contrails form when hot, humid exhaust mixes with cold air and water condenses and freezes on soot particles.
- Persistent contrails can spread into cirrus that trap outgoing heat.
- Fewer soot particles mean fewer, larger ice crystals that disappear sooner.
- NASA and DLR found cleaner-burning sustainable fuels produced 50%–70% fewer ice crystals at cruise.
- Routing around ice-supersaturated air can avoid persistent contrails.

Key equations

$$N = EI \times m_f$$

`N=EI× m_f`

Ice crystals from emission index and fuel

$$N' = N(1 - r)$$

`N^=N(1-r)`

After a reduction r

$$r \in [0.5, 0.7]$$

NASA-DLR range

$$\Delta T \propto F$$

Worked examples, step by step

Example 6.1 A sample emission index of 10^{15} ice crystals per kg of fuel. With a 50% reduction?

1. $10^{15} \times 0.5$.

Answer: 5×10^{14} per kg.

Example 6.2 With a 70% reduction?

1. $10^{15} \times 0.3$.

Answer: 3×10^{14} per kg.

Example 6.3 A flight burns 15,000 kg of fuel at cruise (sample). Crystals at the 70% reduction?

1. $3 \times 10^{14} \times 15{,}000$.

Answer: 4.5×10^{18}.

Practice problems

Work each on paper first, then check.

1. Why do contrails warm at night?

   They trap outgoing infrared with no sunlight to reflect.

2. What seeds contrail ice?

   Soot and other particles.

3. Reduction from 5×10^{14} to 3×10^{14}?

   40%.

4. One operational fix?

   Route around ice-supersaturated air.

Common misconceptions

Myth: Contrails are just water, so harmless.

Actually: They can add warming.

Myth: All contrails persist.

Actually: Only in ice-supersaturated air.

Myth: Only CO_2 matters.

Actually: Non-CO_2 effects are significant.

Flashcards

Contrail

Condensation trail.

Contrail cirrus

Spread persistent contrails.

Ice supersaturation

Air able to grow ice.

Soot

Carbon particles.

Emission index

Amount per kg of fuel.

Non-CO_2 forcing

Warming besides CO_2.

Self-check quiz

1. 50% reduction...

5×10^{14}

5×10^{15}

10^{14}

0

5×10^{14}. × 0.5.

2. NASA-DLR range...

50%–70%

5%–7%

90%–100%

20%

50%–70%. NASA.

3. Crystals per flight…

4.5×10^{18}

4.5×10^{14}

3×10^{14}

1.5×10^{19}

4.5×10^{18}. × 15,000.

4. Contrail ice forms on…

soot particles

CO_2

nitrogen

ozone

soot particles. Nucleation.

Try this quiz again

How this helps save the planet

NASA reports that cleaner-burning jet fuels made from sustainable sources can produce 50%–70% fewer ice crystal contrails at cruising altitude, from joint NASA and DLR (German Aerospace Center) research.

NASA notes ice-crystal contrails can linger in the upper atmosphere for hours and affect the way Earth is heated and cooled.

On Saving Planets: Earth Observation · Heat Transfer

Sources: NASA: NASA-DLR study finds sustainable aviation fuel can reduce contrails (2021) (https://www.nasa.gov/news-release/nasa-dlr-study-finds-sustainable-aviation-fuel-can-reduce-contrails/)

Free learning resources

- NASA: NASA-DLR study finds sustainable aviation fuel can reduce contrails (2021) (https://www.nasa.gov/news-release/nasa-dlr-study-finds-sustainable-aviation-fuel-can-reduce-contrails/): NASA study.
- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.

☐ **I finished this unit**

Electric and Hybrid Propulsion

Battery energy density, drivetrain efficiency, electric range, and where hybrid systems help.

Learning objectives

By the end of this unit you can:

- Compare battery and fuel energy density.
- Account for drivetrain efficiency.
- Compute electric aircraft range.
- Identify suitable missions.

Key concepts

- Jet fuel stores about 43 MJ/kg (11,944 Wh/kg); today's batteries store a few hundred Wh/kg (textbook values).
- Electric drivetrains convert energy far more efficiently (about 90%) than turbines (about 35%), shrinking the gap (textbook values).
- Battery-electric range is R = (e η/g)(L/D)(m_b/m).
- Batteries don't get lighter as they discharge, unlike fuel.
- NASA says electrified aircraft propulsion offers new possibilities for reducing fuel and energy use, from small passenger aircraft to single-aisle transports.

Key equations

$$R = \frac{e\eta}{g}\frac{L}{D}\frac{m_b}{m}$$

`R=e/gL/D(m_b)/(m)`

Battery-electric range

$$\frac{e_{fuel}}{e_{batt}}$$

Energy-density ratio

$$e = 250\ \mathrm{Wh/kg} = 9\times10^{5}\ \mathrm{J/kg}$$

`e=250\ Wh/kg=9×10^5\ J/kg`

Sample battery

$$1\ \mathrm{Wh} = 3600\ \mathrm{J}$$

`1\ Wh=3600\ J`

Conversion

Worked examples, step by step

Example 7.1 Jet fuel at 43 MJ/kg in Wh/kg, and ratio to a 250 Wh/kg battery?

1. $43 \times 10^6/3600 = 11{,}944$ Wh/kg.
2. 11,944/250.

Answer: 47.8 times.

Example 7.2 Adjust for efficiency: turbine 0.35, electric 0.9.

1. $47.8 \times 0.35/0.9$.

Answer: About 18.6 times.

Example 7.3 Range with $e = 250$ Wh/kg, $\eta = 0.8$, $L/D = 15$, battery fraction 0.3.

1. $9 \times 10^5 \times 0.8/9.80665 \times 15 \times 0.3$.

Answer: About 330 km.

Practice problems

Work each on paper first, then check.

1. Range if battery energy doubles to 500 Wh/kg?

   About 661 km.

2. 250 Wh/kg in J/kg?

   9×10^5.

3. Why do hybrids help?

   Electric power boosts takeoff and climb while fuel provides range.

4. Best first missions?

   Short regional and training flights.

Common misconceptions

Myth: Batteries will soon equal jet fuel.

Actually: The gap is large even after efficiency.

Myth: Electric means zero emissions.

Actually: It depends on the grid.

Myth: Battery weight falls in flight.

Actually: It stays constant.

Flashcards

Specific energy

Energy per mass.

Drivetrain efficiency

Battery-to-shaft efficiency.

Hybrid-electric

Fuel plus electric power.

Battery fraction

Battery over aircraft mass.

Wh/kg

Battery specific energy unit.

Grid intensity

CO_2 per kWh.

Self-check quiz

1. Energy ratio...

47.8

4.78

478

18.6

47.8. 11,944/250.

2. Efficiency-adjusted...

18.6

47.8

2.6

100

18.6. × 0.35/0.9.

3. Electric range...

≈ 330 km

≈ 33 km

≈ 3300 km

≈ 660 km

≈ 330 km. Formula.

4. Doubled energy range...

≈ 661 km

≈ 330 km

≈ 1320 km

≈ 165 km

≈ 661 km. Linear.

Try this quiz again

How this helps save the planet

NASA says electrified aircraft propulsion offers new possibilities for reducing fuel and energy usage in aviation from small passenger aircraft to single-aisle transports, using new technologies,

concepts, test aircraft and ground facilities.

This unit's range equation shows why the first electric aircraft fly short routes. Energy densities here are textbook values.

On Saving Planets: Circuits · Solutions

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.
- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.

☐ **I finished this unit**

Hydrogen Aircraft

Hydrogen’s energy per mass and volume, tank sizing, water emissions, and design trade-offs.

Learning objectives

By the end of this unit you can:

- Compare hydrogen and jet fuel by mass and volume.
- Size a hydrogen tank volume.
- Compute water produced.
- Explain design trade-offs.

Key concepts

- Hydrogen holds about 120 MJ/kg, 2.8 times jet fuel, but liquid hydrogen is only about 70.8 kg/m³ (textbook values).
- Per liter, liquid hydrogen holds about 8.5 MJ versus about 34.4 MJ for jet fuel, so tanks are about four times larger.
- Burning or using hydrogen in a fuel cell makes water, about 8.9 kg per kg of hydrogen, and no CO_2 at the aircraft.
- Cryogenic tanks are bulky and heavy, shaping the whole aircraft.
- Green hydrogen depends on clean electricity for electrolysis.

Key equations

$$e_v = \rho\, e_m$$

`e_v=ρ e_m`

Energy per volume

$$V = \frac{E}{e_v}$$

`V=(E)/(e_v)`

Tank volume

$$m_{H_2O} = 8.94\, m_{H_2}$$

`m_H_20=8.94 m_H_2`

Water from hydrogen

$$\frac{e_{H_2}}{e_{jet}} = \frac{120}{43}$$

`_H_2e_jet=120/43`

Mass ratio

Worked examples, step by step

Example 8.1 Hydrogen vs jet fuel by mass?

1. 120/43.

Answer: 2.79 times more per kg.

Example 8.2 Volumetric energy of liquid hydrogen?

1. 70.8 × 120/1000.

Answer: 8.50 MJ/L.

Example 8.3 Tank-volume ratio vs jet fuel (0.8 kg/L, textbook)?

1. 34.4/8.50.

Answer: About 4.05 times larger.

Practice problems

Work each on paper first, then check.

1. Water from 100 kg of hydrogen?

   About 894 kg.

2. Jet fuel volumetric energy?

   0.8 × 43 = 34.4 MJ/L.

3. Why are hydrogen tanks heavy?

   Insulated cryogenic walls.

4. When is hydrogen low-carbon?

   When made with clean energy.

Common misconceptions

Myth: Hydrogen is light, so tanks are small.

Actually: Low density means big tanks.

Myth: Hydrogen aircraft emit nothing.

Actually: They emit water vapor, which can form contrails.

Myth: All hydrogen is green.

Actually: Most today is made from fossil gas.

Flashcards

LH_2

Liquid hydrogen.

Cryogenic

Very cold storage.

Fuel cell

Electrochemical power source.

Electrolysis

Splitting water with electricity.

Volumetric energy

Energy per volume.

Green hydrogen

Made with clean power.

Self-check quiz

1. Mass ratio...

2.79

0.36

4.05

120

2.79. 120/43.

2. MJ/L of LH_2...

8.50

34.4

120

0.85

8.50. 70.8 × 0.12.

3. Tank ratio...

≈ 4

≈ 0.25

≈ 1

≈ 40

≈ 4. 34.4/8.5.

4. Water per kg H_2...

≈ 8.9 kg

≈ 1 kg

≈ 18 kg

0

≈ 8.9 kg. 18.015/2.016.

Try this quiz again

How this helps save the planet

NASA's Sustainable Flight National Partnership works across advanced vehicle technologies, efficient operations and sustainable aviation fuels; this unit adds hydrogen as a further option, where tank volume is the main design challenge.

Hydrogen values in this unit are textbook values, not NASA figures.

On Saving Planets: General Chemistry I · Thermodynamics

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

Free learning resources

- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.
- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.

- [ ] **I finished this unit**

Operations, Noise and Air Quality

Efficient taxi and trajectories, decibel arithmetic, airport noise, local air quality and leaded aviation gasoline.

Learning objectives

By the end of this unit you can:

- Estimate taxi fuel savings.
- Add sound levels in decibels.
- Apply the inverse-square law.
- Explain the leaded-fuel issue.

Key concepts

- Operations matter: single-engine taxi, continuous descents and optimal trajectories cut fuel with today's aircraft.
- Decibels add logarithmically: two equal sources are 3 dB louder, not twice the number.
- In open air, sound level drops about 6 dB per doubling of distance.
- Engine NOx, particles and CO affect air quality near airports.
- EPA says most aircraft using leaded fuel are piston-engine aircraft carrying 2–10 passengers; commercial jets don't use leaded fuel.

Key equations

$$L = 10 \log_{10} \sum 10^{L_i/10}$$

`L=10_1010^L_i/10`

Adding sound levels

$$\Delta L = 20 \log_{10}(r_2/r_1)$$

`Δ L=20_10(r_2/r_1)`

Spherical spreading

$$m_f = \dot{m}_f t$$

`m_f= m_ft`

Fuel used

$$m_{CO_2} = 3.16\, m_f$$

`m_CO_2=3.16 m_f`

CO_2 per kg fuel (textbook)

Worked examples, step by step

Example 9.1 Two 80 dB sources together?

1. $10 \log_{10}(2 \times 10^8)$.

Answer: 83.0 dB.

Example 9.2 Level drop from doubling distance?

1. $20 \log_{10} 2$.

Answer: 6.02 dB.

Example 9.3 Taxi 10 minutes on one engine instead of two at 0.1 kg/s each (sample). Fuel and CO_2 saved?

1. $0.1 \times 600 = 60$ kg.
2. 60×3.16.

Answer: 60 kg of fuel, about 190 kg of CO_2.

Practice problems

Work each on paper first, then check.

1. Ten equal 70 dB sources?

   80 dB.

2. Drop when distance quadruples?

   12.0 dB.

3. Fuel for two engines over 10 minutes?

   120 kg.

4. Which aircraft use leaded fuel (EPA)?

Mostly piston-engine aircraft.

Common misconceptions

Myth: Decibels add linearly.

Actually: They add logarithmically.

Myth: Operations can't cut emissions.

Actually: They cut fuel today.

Myth: Airliners burn leaded fuel.

Actually: EPA says commercial jets don't.

Flashcards

Decibel

Log measure of sound.

Inverse-square law

Intensity falls with r^2.

Single-engine taxi

Taxi on one engine.

Continuous descent

Idle descent without level-offs.

NOx

Nitrogen oxides.

Avgas

Aviation gasoline.

Self-check quiz

1. Two 80 dB...

83.0 dB

160 dB

80 dB

86 dB

83.0 dB. +3 dB.

2. Doubling distance…

−6.02 dB

−3 dB

−10 dB

−20 dB

−6.02 dB. 20 log 2.

3. CO_2 saved taxiing…

≈ 190 kg

≈ 60 kg

≈ 19 kg

≈ 600 kg

≈ 190 kg. 60 × 3.16.

4. Leaded fuel users…

piston aircraft

airliners

rockets

helicopters only

piston aircraft. EPA.

Try this quiz again

How this helps save the planet

EPA says the majority of aircraft operating on leaded fuel are piston-engine aircraft, typically carrying 2–10 passengers, and that jets used for commercial transport do not use leaded fuel.

EPA has issued a final determination that lead emissions from certain aircraft engines endanger public health and welfare, triggering duties for EPA and the FAA to set standards.

On Saving Planets: Solutions · Aircraft Performance

Sources: U.S. EPA: Regulations for lead emissions from aircraft (https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-lead-emissions-aircraft)

Free learning resources

- U.S. EPA: Regulations for lead emissions from aircraft (https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-lead-emissions-aircraft): EPA page.
- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture.

☐ **I finished this unit**

Pathways to Net Zero

Traffic growth, efficiency, SAF, new aircraft and offsets combined into scenarios toward 2050.

Learning objectives

By the end of this unit you can:

- Project traffic growth.
- Combine reductions multiplicatively.
- Build a simple wedge scenario.
- Discuss policy tools.

Key concepts

- Emissions = traffic × energy per traffic unit × carbon per energy.
- Growth compounds: 3% a year doubles traffic in about 24 years (sample rate).
- Reductions multiply: (1 − efficiency gain) × (1 − SAF lifecycle saving).
- Remaining emissions need new aircraft, more SAF, or removals.
- DOE notes ICAO's CORSIA caps net CO_2 from international aviation at 2020 levels through 2035.

Key equations

$$E = T \times \frac{MJ}{T} \times \frac{CO_2}{MJ}$$

`E=T×MJ/T×(CO_2)/(MJ)`

Emissions identity

$$T_n = T_0(1+g)^n$$

`T_n=T_0(1+g)^n`

Traffic growth

$$E' = E(1-a)(1-b)$$

`E^=E(1-a)(1-b)`

Combined reductions

$$n_2 = \frac{\ln 2}{\ln(1+g)}$$

`n_2=(2)/((1+g))`

Doubling time

Worked examples, step by step

Example 10.1 Traffic grows 3% a year from 2026 to 2050 (sample). Growth factor?

1. 1.03^{24}.

Answer: 2.03.

Example 10.2 With a 25% efficiency gain, emissions relative to today?

1. 2.033 × 0.75.

Answer: 1.52.

Example 10.3 Add SAF with a 50% fleet-wide lifecycle saving.

1. 1.525 × 0.5.

Answer: 0.762, still 76% of today's level.

Practice problems

Work each on paper first, then check.

1. Doubling time at 3%?

   23.4 years.

2. Saving needed to reach 0 from 0.762?

   The full remainder: new aircraft, more SAF and removals.

3. Years from 2026 to 2050?

   24.

4. What does CORSIA cap?

   Net international aviation CO_2 at 2020 levels through 2035.

Common misconceptions

Myth: Reductions add.

Actually: They multiply.

Myth: Efficiency alone reaches net zero.

Actually: Growth outpaces it.

Myth: Offsets cut emissions at the engine.

Actually: They compensate elsewhere.

Flashcards

Net zero

Emissions balanced by removals.

Wedge

Slice of a reduction plan.

CORSIA

ICAO offsetting scheme.

Traffic growth

Rise in passenger-km.

Removal

Taking CO_2 from the air.

Scenario

Consistent set of assumptions.

Self-check quiz

1. Growth factor...

2.03

1.72

1.03

3.0

$2.03.\ 1.03^{24}$.

2. With efficiency...

1.52

2.03

0.76

1.0

1.52. × 0.75.

3. With SAF too...

0.762

0.25

1.52

0

0.762. × 0.5.

4. Net-zero goal year...

2050

2030

2035

2100

2050. NASA.

Try this quiz again

How this helps save the planet

NASA says its Sustainable Flight National Partnership works with industry, academia and other agencies toward the aviation community's goal of net-zero carbon emissions by 2050.

DOE notes that ICAO's CORSIA caps net CO_2 from international aviation at 2020 levels through 2035.

On Saving Planets: Solutions · Capstone Design

Sources: NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/) · U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel)

Free learning resources

- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA SFNP.
- U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel): DOE SAF page.

☐ **I finished this unit**

Problem Sets

These practice problems live inside each unit. Work on paper first, then open the answer.

1. Aviation and Climate: Counting CO_2
   4 problems
2. Efficiency Metrics
   4 problems
3. Aerodynamic Efficiency
   4 problems
4. Engine Efficiency
   4 problems
5. Sustainable Aviation Fuels
   4 problems
6. Contrails and Non-CO_2 Effects
   4 problems
7. Electric and Hybrid Propulsion
   4 problems
8. Hydrogen Aircraft
   4 problems
9. Operations, Noise and Air Quality
   4 problems
10. Pathways to Net Zero
    4 problems

The lab (Sustainable aviation lab)

The lab is the hands-on part of the course. Here it is free and for practice only, with no credit.

Every lab runs in a spreadsheet or a free simulation, so there are no fuel, battery or hydrogen hazards. Do not handle fuels, batteries or pressurized gases for this course. Take screen breaks, sit with good posture, and keep cables out of walkways.

Safety reference: OSHA: Walking-working surfaces (slip, trip and fall hazards) (https://www.osha.gov/walking-working-surfaces)

Lab A: Flight CO_2 calculator

WEEK 1

Goal: Build a spreadsheet that turns fuel burned into CO_2 and CO_2 per passenger-km.

$$m = 9.75V$$

`m=9.75V`

EIA factor

Procedure

1. Enter fuel in gallons for three sample flights.
2. Compute CO_2 with EIA's 9.75 kg/gal.
3. Divide by passengers × km.
4. Compare short and long flights.

Data table

Fuel (gal)	CO_2 (kg)
1000	9750
5000	48,750
20,000	195,000

Computed sample values.

Sample calculation

1. 5000 × 9.75 = 48,750 kg.
2. 20,000 × 9.75 = 195,000 kg.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

U.S. EIA: Carbon dioxide emissions coefficients (https://www.eia.gov/environment/emissions/co2_vol_mass.php)

Planet link: EIA: 9.75 kg CO_2 per gallon of jet fuel. U.S. EIA: Carbon dioxide emissions coefficients (https://www.eia.gov/environment/emissions/co2_vol_mass.php)

- [ ] **I completed this lab (wet or virtual)**

Lab B: L/D and fuel burn

WEEK 4

Goal: See how lift-to-drag ratio changes fuel for a 3000 km trip.

$$W_f/W_i = 1 - e^{-Rc/(V\,L/D)}$$

```
W_f/W_i=1-e^-Rc/(V L/D)
```

Fuel fraction

Procedure

1. Enter R = 3000 km, V = 230 m/s, c = 0.6 /h.
2. Compute the fuel fraction for L/D = 15, 17 and 20.
3. Compute the saving relative to L/D = 17.
4. Add aspect-ratio effects on induced drag.

Data table

L/D	Fuel fraction
15	0.135
17	0.120
20	0.103

Computed sample values.

Sample calculation

1. 1 − e^(−0.1449) = 0.135.
2. 1 − e^(−0.1087) = 0.103.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/)

Planet link: NASA's X-plane demonstrator tests an ultra-efficient aerodynamic design. NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

- [ ] **I completed this lab (wet or virtual)**

Lab C: Propulsive efficiency explorer

WEEK 5

Goal: Compute propulsive and overall efficiency across exhaust velocities.

$$\eta_p = 2/(1 + V_e/V_0)$$

_p=2/(1+V_e/V_0)

Propulsive efficiency

Procedure

1. Enter V_0 = 230 m/s and η_th = 0.5.
2. Compute η_p for V_e = 400, 350 and 300 m/s.
3. Compute overall efficiency.
4. Relate to bypass ratio.

Data table

V_e (m/s)	η_p	η_o
400	0.730	0.365
350	0.793	0.397
300	0.868	0.434

Computed sample values.

Sample calculation

1. 2/(1 + 350/230) = 0.793.
2. 0.5 × 0.793 = 0.397.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/)

Planet link: NASA: Hybrid Thermally Efficient Core develops high-power-density turbine cores. NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

- [ ] **I completed this lab (wet or virtual)**

Lab D: SAF blend calculator

WEEK 7

Goal: Compute lifecycle savings for blends and SAF reductions.

$$s = b \times r$$

s=b× r

Blend saving

Procedure

1. Enter blends of 10%, 30% and 50%.
2. Enter a SAF lifecycle reduction of 50%, then 80%.
3. Compute the saving and CO_2 saved per 1000 gallons.
4. Compare with the Grand Challenge goals.

Data table

Blend	Saving at r = 50%	kg CO_2 saved per 1000 gal
10%	5%	487.5
30%	15%	1462.5
50%	25%	2437.5

Computed sample values.

Sample calculation

1. 0.3 × 0.5 = 15%.
2. 9750 × 0.25 = 2437.5 kg.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel)

Planet link: DOE: SAF can be blended at 10% to 50% depending on pathway. U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel)

- [ ] **I completed this lab (wet or virtual)**

Lab E: Electric aircraft range

WEEK 10

Goal: Compute battery-electric range for several battery energy densities.

$$R = (e\eta/g)(L/D)(m_b/m)$$

`R=(e/g)(L/D)(m_b/m)`

Electric range

Procedure

1. Enter η = 0.8, L/D = 15, battery fraction 0.3.
2. Compute range for 250, 400 and 500 Wh/kg.
3. Compare with a 300 km regional route.
4. Change the battery fraction.

Data table

e (Wh/kg)	Range (km)
250	330
400	529
500	661

Computed sample values.

Sample calculation

1. 400 × 3600 × 0.8/9.80665 × 15 × 0.3 = 529 km.
2. 500 Wh/kg doubles the 250 Wh/kg range.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/)

Planet link: NASA: electrified aircraft propulsion can cut fuel and energy use. NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/)

- [ ] **I completed this lab (wet or virtual)**

Lab F: Net-zero wedge model

WEEK 14

Goal: Explore warming in PhET Greenhouse Effect, then build a 2026–2050 aviation scenario.

$$E = (1+g)^n(1-a)(1-b)$$

E=(1+g)^n(1-a)(1-b)

Scenario emissions

Procedure

1. In PhET Greenhouse Effect, add greenhouse gases and watch the temperature respond.
2. Enter 3% traffic growth for 24 years.
3. Apply a 25% efficiency gain and 50% SAF saving.
4. Find the growth rate at which the two measures hold emissions flat.

Data table

Case	Emissions vs today
Growth only	2.03
+ efficiency	1.52
+ SAF	0.762

Computed sample values.

Sample calculation

1. $1.03^{24} = 2.033$.
2. $2.033 \times 0.75 \times 0.5 = 0.762$.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

PhET: Greenhouse Effect (https://phet.colorado.edu/en/simulations/greenhouse-effect)

Planet link: NASA: the aviation community's goal is net-zero carbon emissions by 2050. NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-natio

nal-partnership/)

- [ ] **I completed this lab (wet or virtual)**

Exam prep practice sets

Time yourself: about 10 minutes per problem. Then compare with the full solutions.

Midterm practice set (Units 1–5)

1. CO_2 from 2000 gallons of jet fuel?
    1. 2000 × 9.75.

    Answer: 19,500 kg.

2. g CO_2 per passenger-km for 19,500 kg, 150 passengers, 1000 km?
    1. 19,500,000/150,000.

    Answer: 130 g.

3. Fuel fraction for 3000 km at L/D = 15 (Unit 3 values)?
    1. 1 − e^(−0.1449).

    Answer: 0.135.

4. η_p for V_0 = 250, V_e = 350 m/s?
    1. 2/(1 + 1.4).

    Answer: 0.833.

5. Saving from a 40% blend at 70% lifecycle reduction?
    1. 0.4 × 0.7.

    Answer: 28%.

Final practice set (Units 1–10)

1. Ice crystals after a 60% cut from 10^{15} per kg?
    1. 10^{15} × 0.4.

    Answer: 4 × 10^{14} per kg.

2. Electric range with 300 Wh/kg (Unit 7 values)?

    1. 330.4 × 1.2.

    Answer: About 396 km.

3. Liquid-hydrogen volume for 1000 MJ?

    1. 1000/8.50.

    Answer: 118 L.

4. Three equal 75 dB sources?

    1. 75 + 10 $\log_{10} 3$.

    Answer: 79.8 dB.

5. Growth factor at 2% for 24 years?

    1. 1.02^{24}.

    Answer: 1.61.

6. Emissions vs today at 2% growth, 25% efficiency, 50% SAF?

    1. 1.608 × 0.75 × 0.5.

    Answer: 0.603.

Formula sheet

$$m_{CO_2} = 9.75 V_{gal},\ m_{CO_2} = 3.16 m_f$$

$$\mathrm{CO_2/pkm} = m_{CO_2}/(n_{pax} d)$$

$$W_f/W_i = 1 - e^{-Rc/(V\,L/D)},\ C_{D_i} = C_L^2/(\pi e A R)$$

$$\eta_p = 2/(1 + V_e/V_0),\ \eta_o = \eta_{th}\eta_p$$

$$s = b\,r$$

$$N = EI\,m_f,\ N' = N(1 - r)$$

$$R = (e\eta/g)(L/D)(m_b/m)$$

$$e_v = \rho e_m,\ m_{H_2O} = 8.94 m_{H_2}$$

$$L = 10\log_{10}\sum 10^{L_i/10},\ \Delta L = 20\log_{10}(r_2/r_1)$$

$$E = (1+g)^n(1-a)(1-b)$$

Constants

Constant	Value
Standard gravity	$g = 9.80665\ m/s^2$
Jet fuel CO_2 (EIA)	9.75 kg CO_2 per gallon (21.50 lb)
Jet fuel heating value (textbook value)	43 MJ/kg
Hydrogen heating value (textbook value)	120 MJ/kg
Liquid hydrogen density (textbook value)	$70.8\ kg/m^3$
Gallon	3.785411784 L

Source: NIST: CODATA value, standard acceleration of gravity (https://physics.nist.gov/cgi-bin/cuu/Value?gn)

Free texts and sources

Use these free lectures, data pages and simulations alongside the course.

- MIT OpenCourseWare 16.885J Aircraft Systems Engineering (Fall 2004), Lecture 8: Environmental Factors (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2004/pages/lecture-notes/): Free MIT lecture notes.
- NASA Aeronautics: Sustainable Flight National Partnership (https://www.nasa.gov/aeronautics/sustainable-flight-national-partnership/): NASA program.
- U.S. DOE Alternative Fuels Data Center: Sustainable aviation fuel (https://afdc.energy.gov/fuels/sustainable-aviation-fuel): DOE SAF data.
- U.S. EIA: Carbon dioxide emissions coefficients (https://www.eia.gov/environment/emissions/co2_vol_mass.php): EIA emission factors.
- NASA: NASA-DLR study finds sustainable aviation fuel can reduce contrails (2021) (https://www.nasa.gov/news-release/nasa-dlr-study-finds-sustainable-aviation-fuel-can-reduce-contrails/): NASA contrail study.
- PhET: Greenhouse Effect (https://phet.colorado.edu/en/simulations/greenhouse-effect): Radiation balance.

Glossary

Aspect ratio
Span squared over wing area.

Avgas
Aviation gasoline for piston engines.

Blend limit
Maximum SAF share in jet fuel.

CORSIA
ICAO carbon offsetting scheme.

Contrail

Condensation trail of ice crystals.

Decibel
Logarithmic sound measure.

Electrified propulsion
Electric or hybrid aircraft power.

Emission factor
CO_2 per unit of fuel.

Energy intensity
Energy per passenger-km.

Induced drag
Drag caused by lift.

Lifecycle emissions
Well-to-wake CO_2.

Liquid hydrogen
Cryogenic hydrogen fuel.

Load factor
Passengers over seats.

Net zero
Emissions balanced by removals.

Non-CO_2 effects
Warming from contrails, NOx and particles.

Passenger-km
One passenger carried one km.

Propulsive efficiency
Share of jet power producing thrust.

SAF
Sustainable aviation fuel.

Soot
Carbon particles in exhaust.

Specific energy
Energy per unit mass.

Self-assessment rubric

No grade or credit is given. Use this to judge honestly where you are in each unit.

Level	What it looks like
4 · Mastery	Accounts for CO_2 and non-CO_2 effects with correct units and baselines, combines reductions correctly, and explains trade-offs between options in plain words.
3 · Proficient	Solves the practice and exam sets with minor slips and checks units.
2 · Developing	Follows worked examples but mixes up combustion and lifecycle CO_2 or adds reductions instead of multiplying.
1 · Beginning	Quotes savings without baselines or units; needs to revisit the units.

Suggested weighting if you want a score

Part	Weight
Practice problems	20%
Labs	25%
Midterm practice set	25%
Final practice set	30%

Aim for level 3 or better in every unit before moving to the next course.

Related courses

- Capstone (aircraft or CubeSat) AERO 490
- Propulsion AERO 410
- Flight Dynamics & Controls AERO 420
- All courses