

Large emission avoidance potential in improved commercial air transport efficiency

Corresponding Author: Professor Stefan Gössling

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Professor Gössling,

First of all, please allow me to apologise for the delay in sending a decision on your manuscript titled "Large emission avoidance potential in improved air transport efficiency". It has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to

- address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid, or relevant to the editorial threshold as outlined below)

AND

- meet our editorial thresholds as outlined below,

then we would be happy to look at a substantially revised manuscript.

In the following, we list our main editorial concerns.

***Outline and justify your method and data in detail, including all calculation assumptions, choice of load factors and distance correction, provide more details on fuel consumption data, and address potential bias and representatives of your data.

***Discuss your findings and approach in detail, including limitations, potential NOx emissions impact, and outline a roadmap for implementing efficiency strategies, feasibility, and timelines.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Martina Grecequet, PhD
Senior Editor,
Communications Earth & Environment
Consulting Editor
Communications Sustainability

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REVIEWER COMMENTS:

Reviewer #2 (Remarks to the Author):

Gössling et al. present an assessment of the CO₂ efficiency of global passenger air transport by analyzing over 27 million flights across more than 26,000 city pairs in 2023. The study reveals large variability in emissions per revenue passenger kilometer across different aircraft types, routes, airlines, and regions, and estimates the potential for emission reduction if operations were optimized to achieve best-practice efficiency levels.

I found the authors' approach interesting, as it highlights an important and underexplored opportunity for emission mitigation through operational improvements. However, several aspects need to be addressed before the paper is ready for publication.

1. The paper would benefit from a clearer discussion on the practical roadmap for implementing the proposed efficiency-enhancing strategies in support of sustainability goals. For instance, achieving a 95% load factor may be more feasible in the short term compared to fleet replacement with only the most efficient aircraft types, which is unlikely to be achievable in the short or even medium term. A more detailed discussion on the feasibility and timelines of these strategies is recommended.

2. Building on the previous point, it would be valuable to discuss whether existing climate projections account for such improvements in air transport efficiency. If not, it is suggested that the authors discuss how the inclusion of these efficiency gains might change the existing projections (e.g., the well-known projection here: <https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/>, attributing 10% emission reduction to operations and infrastructure), especially about key milestone years (e.g., 2035, 2050)?

3. While the focus is on CO₂, the analysis may also have implications for non-CO₂ climate effects (e.g., NO_x emissions-induced effects). As fuel consumption is directly tied to NO_x emissions, strategies that reduce fuel burn could also mitigate non-CO₂ climate effects (though it also has a dependency on the atmospheric background conditions). Such analysis could strengthen the paper by either quantifying potential NO_x climate impact reductions (e.g., in terms of climate metrics such as GWP) or including a discussion on this point.

4. The statement that "the replacement of Jet A-1 with SAF ignores non-CO₂ components" may be somewhat misleading. SAF can reduce contrail warming by lowering soot particle emissions. Clarification of this point is necessary to ensure alignment with current scientific understanding.

5. A dedicated section on data collection and sources is recommended. In particular, the GitHub link referenced in the paper appears to be non-existent.

6. Do the authors expect the patterns illustrated in Figures 1 and 2 to remain similar over different years? A brief discussion on the generalizability of the findings would be beneficial in contextualizing the broader relevance of the results.

7. It is recommended to provide a more detailed discussion on the limitations of the current analysis, including the assumptions made and the challenges associated with implementing the proposed strategies.

Reviewer #3 (Remarks to the Author):

The authors use global datasets (ICAO, IATA, FlightGlobal, etc.) to systematically assess and compare the carbon efficiency of worldwide commercial flights in 2023. They explore operational differences across aircraft models, airlines, routes, and regions, and estimate the emission reduction potential from measures like fleet renewal, all-economy layouts, and higher load factors. While the study provides valuable insights and policy implications, several key issues—such as methodological assumptions and the feasibility of the proposed scenarios—still require further clarification.

1. The dataset used covers only 83% of total global RPK and 82% of passengers, which indicates a significant portion of missing data. Given that this missingness is likely to be non-random—for instance, systematically excluding certain countries, routes, or operational categories rather than generic charter flights—how does the study account for potential bias and ensure the reliability and representativeness of its results?

2. Does the manuscript use actual seat configuration data for each flight? Even for the same aircraft type, seat layouts can vary significantly between airlines.

3. The scenarios based on the most efficient aircraft, all-economy layouts, and a 95% load factor seem highly idealized and difficult to achieve in practice, considering cost factors, the need for service differentiation between LCCs and FSCs, and limited demand on certain routes.

4. The use of ICAO's simple distance correction (+50/100/125 km) is rather crude. In reality, the ratio of actual flight distance to great-circle distance depends on multiple factors such as weather, airspace restrictions, and airport congestion, leading to substantial variation. Even for flights with the same great-circle distance, the actual flown distance may differ substantially depending on the country or specific route, as a result of varying airspace structures and operational conditions.

5. The manuscript uses airline-level average load factors, which can introduce significant errors into emission efficiency calculations. For example, consider two flights: one of 800 km at a 60% load factor and another of 8,000 km at a 100% load factor—the average load factor is 80%. If, instead, the 800 km flight operates at 100% and the 8,000 km flight at 60%, the overall average remains the same, yet the combined carbon efficiency can differ by more than 30%. This highlights the substantial impact of load factor distribution on emission estimates, which the current methodology does not adequately capture.

6. The details of the fuel consumption calculation are not clearly stated.

7. The use of formula screenshots in the Word manuscript is not appropriate.

In summary, data gaps and crude calculations in the current manuscript make it difficult to ensure the accuracy of the results. Improving the precision of calculations is strongly recommended.

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Version 1:

Decision Letter:

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Dear Professor Gössling,

Your manuscript titled "Large emission avoidance potential in improved commercial air transport efficiency" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Martina Grecequet, PhD
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REVIEWER COMMENTS:

Reviewer #2 (Remarks to the Author):

Gössling et al. have sufficiently addressed my concerns and incorporated discussions on the raised points. I have no further comments and recommend acceptance of the manuscript.

Reviewer #3 (Remarks to the Author):

We appreciate the authors' careful reply and their use of citypair–airline–aircraft–level load factors, which in principle improves measurement precision over airline-level averages; however, our remaining concern is about global coverage and missingness, which directly affects the construction of intensity: T100I (AirlineData) provides annual flight-specific means but is limited to USA/Canada traffic, while ICAO TFS is global yet does not include all airlines, so we ask (i) whether flight-level load factors exhibit missing values outside North America and for carriers not covered by ICAO TFS; (ii) how such missingness is handled (imputation hierarchy, regional/ASK weighting, temporal interpolation, multiple imputation, and whether uncertainty from imputation is propagated to standard errors).

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Version 2:

Decision Letter:

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Dear Professor Gössling,

Your manuscript titled "Large emission avoidance potential in improved commercial air transport efficiency" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Martina Grecequet, PhD

Senior Editor,
Communications Earth & Environment
Consulting Editor,
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #3 (Remarks to the Author):

The authors have addressed my concerns.

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Response to Reviewers:

Large emission avoidance potential in improved commercial air transport efficiency (COMMSENV-25-1886)

Reviewer 2

Gössling et al. present an assessment of the CO₂ efficiency of global passenger air transport by analyzing over 27 million flights across more than 26,000 city pairs in 2023. The study reveals large variability in emissions per revenue passenger kilometer across different aircraft types, routes, airlines, and regions, and estimates the potential for emission reduction if operations were optimized to achieve best-practice efficiency levels.

I found the authors' approach interesting, as it highlights an important and underexplored opportunity for emission mitigation through operational improvements. However, several aspects need to be addressed before the paper is ready for publication.

1. The paper would benefit from a clearer discussion on the practical roadmap for implementing the proposed efficiency-enhancing strategies in support of sustainability goals. For instance, achieving a 95% load factor may be more feasible in the short term compared to fleet replacement with only the most efficient aircraft types, which is unlikely to be achievable in the short or even medium term. A more detailed discussion on the feasibility and timelines of these strategies is recommended.

We agree that a roadmap would be desirable. However, we believe that it is beyond the scope of this paper to engage with a full analysis of the political and business implications of our findings, as the current air transport system is driven by specific mindsets and political frameworks (continued growth, availability of subsidies). The purpose of our paper is to contribute an analysis of the theoretical bounds of the efficiency potential. To develop a roadmap would introduce subjectivity, and likely be criticized by industry as “unfeasible” either way. In this context, we also note that there is no evidence that any of the roadmap-like scenarios for aviation published in Nature journals has been implemented (e.g. Bergero et al. 2023; Dray et al. 2022). The reviewer is however correct that perspectives of “achievability” will vary, which we have now included in the paper in a generic discussion.

Bergero, C., Gosnell, G., Gielen, D., Kang, S., Bazilian, M., & Davis, S. J. (2023). Pathways to net-zero emissions from aviation. *Nature Sustainability*, 6(4), 404-414.

Dray, L., Schäfer, A. W., Grobler, C., Falter, C., Allroggen, F., Stettler, M. E., & Barrett, S. R. (2022). Cost and emissions pathways towards net-zero climate impacts in aviation. *Nature Climate Change*, 12(10), 956-962.

2. Building on the previous point, it would be valuable to discuss whether existing climate projections account for such improvements in air transport efficiency. If

not, it is suggested that the authors discuss how the inclusion of these efficiency gains might change the existing projections (e.g., the well-known projection here: <https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/>, attributing 10% emission reduction to operations and infrastructure), especially about key milestone years (e.g., 2035, 2050)?

Yet, articles usually consider efficiency gains (e.g. Gössling and Humpe 2024). We have added a reference to Waypoint, noting again that there is no evidence of implementation of the measures discussed in Waypoint.

Gössling, S., & Humpe, A. (2024). Net-zero aviation: Transition barriers and radical climate policy design implications. *Science of the Total Environment*, 912, 169107.

3. While the focus is on CO₂, the analysis may also have implications for non-CO₂ climate effects (e.g., NO_x emissions-induced effects). As fuel consumption is directly tied to NO_x emissions, strategies that reduce fuel burn could also mitigate non-CO₂ climate effects (though it also has a dependency on the atmospheric background conditions). Such analysis could strengthen the paper by either quantifying potential NO_x climate impact reductions (e.g., in terms of climate metrics such as GWP) or including a discussion on this point.

We agree, and have noted implied non-CO₂ effects in the paper, but it is difficult to quantify these. Non-CO₂ emissions, on average, have a stronger climate effect than CO₂ itself. However, they only matter at high altitude, which causes them to affect short and long-haul flights differently, as short-haul flights will not fly above 9 km. For reasons of these complexities, the focus of this paper is thus on CO₂.

4. The statement that "the replacement of Jet A-1 with SAF ignores non-CO₂ components" may be somewhat misleading. SAF can reduce contrail warming by lowering soot particle emissions. Clarification of this point is necessary to ensure alignment with current scientific understanding.

Thank you - we have rephrased the sentence, which now reads:

"Efficiency gains have importance, because the replacement of Jet A1 with SAF does not eliminate non-CO₂ components, even though lower soot particle emissions can reduce effective radiative forcing (Märkl et al. 2024). Strategies minimizing fuel use are thus preferable, as they contribute to a reduction in CO₂ as well as non-CO₂ effects."

5. A dedicated section on data collection and sources is recommended. In particular, the GitHub link referenced in the paper appears to be non-existent.

Data sources are presented in Methods, in the Efficiency model section. We use T100I, ICAO TFS, IATA WATS, and FlightGlobal data. If there is any remaining unclarity, please let us know.

We apologize for the non-functional link. This was a place holder for the time being and should now work.

6. Do the authors expect the patterns illustrated in Figures 1 and 2 to remain similar over different years? A brief discussion on the generalizability of the findings would be beneficial in contextualizing the broader relevance of the results.

To answer the question, it would be necessary to recalculate the findings for different years. Given COVID-effects, such calculations with past data may have limited significance. It would thus be more appropriate to re-calculate in the future, when new data becomes available. The data presented is a snapshot of the situation in 2023, though it can generally be expected that there is some stability in the system in the absence of disruptions such as COVID: aircraft are in service for an average period of 25 years, for example, and airlines buy new aircraft continuously rather than replacing their entire fleet. Furthermore, flight distance, which is stated to strongly impact efficiency, is unlikely to change significantly for larger airlines or airports annually - though load factors might, depending also on many complex economic factors, but save disruptions such as COVID, even load factors have been stable historically (Gössling and Humpe 2024). National politics also influence global aviation which will always impact the comparison of annual data. A discussion of the generalizability of the data is included in the new Limitations section.

Gössling, S., & Humpe, A. (2024). Net-zero aviation: Transition barriers and radical climate policy design implications. *Science of the Total Environment*, 912, 169107.

7. It is recommended to provide a more detailed discussion on the limitations of the current analysis, including the assumptions made and the challenges associated with implementing the proposed strategies.

We have now added a discussion on limitations, as well as the challenges associated with implementing a more efficient air transport system.

Reviewer 3

The authors use global datasets (ICAO, IATA, FlightGlobal, etc.) to systematically assess and compare the carbon efficiency of worldwide commercial flights in 2023. They explore operational differences across aircraft models, airlines, routes, and regions, and estimate the emission reduction potential from measures like fleet renewal, all-economy layouts, and higher load factors. While the study provides valuable insights and policy implications, several key issues—such as methodological assumptions and the feasibility of the proposed scenarios—still require further clarification.

1. The dataset used covers only 83% of total global RPK and 82% of passengers, which indicates a significant portion of missing data. Given that this missingness is likely to be non-random—for instance, systematically excluding certain countries, routes, or operational categories rather than generic charter flights—how does the study account for potential bias and ensure the reliability and representativeness of its results?

As a general disclaimer, there is no complete dataset for global aviation. This is a recurrent problem in air transport studies, even those using ADS-B data (Quadros et al. 2022). For example, Klenner et al. (2024) identified 36.2 million commercial flights in 2019, while Teoh et al. (2023) identified 40.2 million in that year. Yet, calculated emissions are higher in Klenner et al. (ibid.), at 920 TgCO₂, while Teoh et al. (ibid.) arrive at 893 TgCO₂. It is not entirely clear how differences can be explained, but Teoh et al. (ibid.) include military flights though Klenner et al. (ibid.) do not. Yet another study, Quadros et al. (2022), assesses “civil aviation”, reporting emissions of 937 TgCO₂ in 2019. The study does not reference the number of flights this refers to. Even though this is the highest emission estimate, Quadros et al. (2022) indicate that their calculated fuel consumption is 12.9% lower than worldwide jet kerosene consumption reported by the International Energy Agency for that year (compared to calculations based on OAG ADS-B data).

Given that Klenner (2024), Teoh et al. (2023), and Quadros et al. (2022) calculate emissions for 2019 – with different results -, these cannot be used for comparison with our dataset for 2023. As we have shown, the study however covers 83% of RPK, and 82% of passengers in comparison to ICAO data. As we have indicated, ICAO claims to cover 99% of air transport services reported for 2023. Our data should thus be reliable in the sense that 83% of RPK and 82% of passengers are accounted for.

We also suggest that our data is not biased, because we use official databases (such as IATA WATS). Consequently, our findings represent the air transport system included in these datasets, and findings are reliable for the system studied, but not representative of “aviation” (which also includes freight, private aviation, military flight, and helicopters and other specialized aircraft). We cannot account for details regarding the missing share of RPK (17%) and passengers (18%) in comparison to ICAO data, but there is no reason to assume that the missing data is systematically excluding “countries, routes, or operational categories”, or that our data use has repercussions for the reliability of the data. While we have discussed the system boundaries of our data - and hence cannot draw conclusions on the representativeness of our results for commercial air passenger transport -, we have now summarized uncertainties in a new limitations section. We have also added “commercial” to the title to be clear from the start that our paper is focused on commercial passenger air transport.

Klenner, J., Muri, H., & Strømman, A. H. (2024). Domestic and international aviation emission inventories for the UNFCCC parties. *Environmental Research Letters*, 19(5), 054019.

Quadros, F. D., Snellen, M., Sun, J. & Dedoussi, I. C. Global civil aviation emissions estimates for 2017–2020 using ADS-B data. *J. Aircr.* 59, 1394–1405 (2022).

Teoh, R., Engberg, Z., Shapiro, M., Dray, L. & Stettler, M. E. The high-resolution Global Aviation Emissions Inventory based on ADS-B (GAIA) for 2019–2021. *Atmos. Chem. Phys.* 24, 725–744 (2024).

2. Does the manuscript use actual seat configuration data for each flight? Even for the same aircraft type, seat layouts can vary significantly between airlines.

Yes, the OAG flight schedule contains the actual cabin layout for each individual flight.

3. The scenarios based on the most efficient aircraft, all-economy layouts, and a 95% load factor seem highly idealized and difficult to achieve in practice, considering cost factors, the need for service differentiation between LCCs and FSCs, and limited demand on certain routes.

This is entirely correct. We assess the theoretical maximum efficiency in the air transport system characterized by the data. In the current air transport system, it is likely only possible to increase efficiencies gradually - without an expectation of ever achieving maximum efficiency, which indeed would be more difficult to achieve for FSCs than LCCs. Knowledge of the theoretical maximum efficiency however makes it possible for airlines and policymakers to implement measures that move the system towards greater efficiency. How this is to be achieved in practice, and to which limits, is a question that we do not pursue in more detail in this paper.

4. The use of ICAO's simple distance correction (+50/100/125 km) is rather crude. In reality, the ratio of actual flight distance to great-circle distance depends on multiple factors such as weather, airspace restrictions, and airport congestion, leading to substantial variation. Even for flights with the same great-circle distance, the actual flown distance may differ substantially depending on the country or specific route, as a result of varying airspace structures and operational conditions.

We do agree, but this is the official measure used in international civil aviation. It seems more appropriate to use the established industry norms than to devise our own that the industry would then criticize. We have however added this concern to the limitations section. Perhaps to add, also with a view to the following comment, our calculations are focused on yearly averages for citypairs, airlines, and aircraft. Hence, daily changes in flight distance because of weather conditions or other factors are averaged out.

5. The manuscript uses airline-level average load factors, which can introduce significant errors into emission efficiency calculations. For example, consider two flights: one of 800 km at a 60% load factor and another of 8,000 km at a 100% load factor—the average load factor is 80%. If, instead, the 800 km flight operates

at 100% and the 8,000 km flight at 60%, the overall average remains the same, yet the combined carbon efficiency can differ by more than 30%. This highlights the substantial impact of load factor distribution on emission estimates, which the current methodology does not adequately capture.

Our data sources for load factors (T100I and ICAO TFS) are specific at the citypair, airline, aircraft level, i.e. our data is more accurate than airline-level averages. As our calculation of efficiencies focuses on city pairs, flight distances are constant, hence calculating average vs. higher load factors should be appropriate. We also added sections for clarity; see following comments.

6.The details of the fuel consumption calculation are not clearly stated.

We have added a section to better explain fuel consumption and calculations. These sections read:

“The emission calculation employs a bottom-up strategy: First, fuel consumption is calculated for each individual flight, accounting for the specific aircraft model, cabin layout, and passenger/cargo load factors. Fuel consumption is derived from a physical aircraft performance model, which calculates fuel consumption for a given aircraft model, considering flight distance and takeoff weight. The total fuel consumption of the flight is then broken down into fuel use per passenger and converted to CO₂ emissions per passenger. All subsequent analyses are based on these individual-flight emission characteristics, allowing for more nuanced results than calculations based on airline-average or city pair-average load factors or performance data.”

“The resulting per-passenger emission intensity enables comparisons of flight efficiency. Figure 8 illustrates the inherent dependence of emission intensity on flight distance, with longer flights generally exhibiting lower emission intensities. This is because takeoff and ascent to cruising altitude - the most fuel-intensive phase of a flight - account for a larger proportion of total fuel burn on short-haul routes.”

7.The use of formula screenshots in the Word manuscript is not appropriate. In summary, data gaps and crude calculations in the current manuscript make it difficult to ensure the accuracy of the results. Improving the precision of calculations is strongly recommended.

We apologize, this is entirely correct, and a result of all of us working in an online google document not allowing for formula inclusion. All formulas are now included. We have also reconsidered these to address the precision concern.

Response to Reviewers (COMMSENV-25-1886A):

Large emission avoidance potential in improved commercial air transport efficiency

Reviewer #2 (Remarks to the Author):

Gössling et al. have sufficiently addressed my concerns and incorporated discussions on the raised points. I have no further comments and recommend acceptance of the manuscript.

Thank you

Reviewer #3 (Remarks to the Author):

We appreciate the authors' careful reply and their use of citypair–airline–aircraft–level load factors, which in principle improves measurement precision over airline-level averages; however, our remaining concern is about global coverage and missingness, which directly affects the construction of intensity: T100I (AirlineData) provides annual flight-specific means but is limited to USA/Canada traffic, while ICAO TFS is global yet does not include all airlines, so we ask (i) whether flight-level load factors exhibit missing values outside North America and for carriers not covered by ICAO TFS; (ii) how such missingness is handled (imputation hierarchy, regional/ASK weighting, temporal interpolation, multiple imputation, and whether uncertainty from imputation is propagated to standard errors).

Thank you for this observation and the concern expressed about load factor accuracy. To address the question, we assessed load factor granularity, calculating the induced error in the comparison of global averages and T100I data. The revised Methods now reads:

“To factor these aspects into the calculation of emissions per RPK, an efficiency model is used that considers distance, aircraft type, and payload (passenger and cargo weight). 2023 data for the efficiency model is derived from:

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- 4) FlightGlobal: similar to IATA WATS, with airline-level data (annual mean load factors) for 178 airlines.

Data consequently has three levels of granularity for load factors:

- **Level 1:** Airline average over one year (52% of all flights).
- **Level 2:** Airline–city pair average over one year (12.4%).
- **Level 3:** Airline–aircraft–city pair average over one year (15.2%).

T100I and ICAO TFS provide level 3 data. From these, level 2 and level 1 averages can be derived by averaging revenue passenger kilometers (RPK) and available seat kilometers (ASK) across aircraft serving a given city pair (level 2) and additionally across all city pairs (level 1, ICAO TFS only). By contrast, IATA WATS and FlightGlobal only provide level 1 data.

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The induced error can be calculated for using global means instead of level 3 values. When bootstrapping 100,000 samples, the per-flight absolute error mean is 0.0406, and the median is 0.0145. The bootstrapped 95% CI for the absolute error mean is [0.0389, 0.0423]. This corresponds to a relative error of 5.38% with a 95% CI of [5.15%, 5.62%]. Notably, this error affects 20.4% of the load factor, as a higher-level granularity for load factors is available for 79.6% of flights.”

The limited error in calculations is also illustrated in Figure 5 and Figure 8 in the manuscript. Figure 5 shows CO₂ intensity by load factor and airline, highlighting a global average load factor of around 0.8. Figure 5 also shows, however, that the largest 30 airlines in the world are not concentrated around 0.8, and thus not or only marginally affected by the use of a global average for calculations where no level 1 to 3 data is available. Similarly, the artifact caused by the average load factor around 0.8 is also visible in Figure 8 and reveals that it is most relevant for short distances below 500 km (brown colour scheme).

To further assess whether the average error is large for specific countries or airlines, we calculated the average error for individual flights (global average in comparison to level 3), finding that it can be large, with a 95% CI of [-0.1473, 0.3812] (Figure 1).

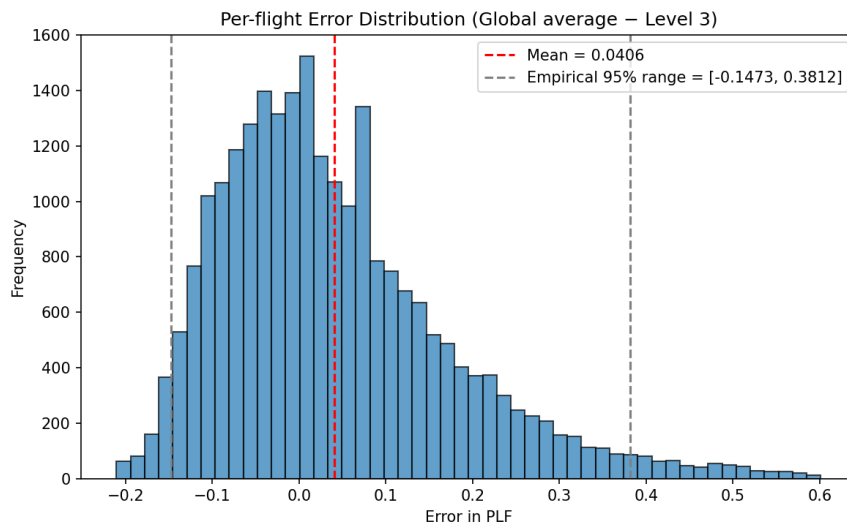


Figure 1: Error distribution, individual flights

Further detailed analysis however shows that the use of global averages has no effect on result presentation or the conclusions drawn in the paper. Countries most affected by the use of a global average load factor represent small, remote, or politically isolated territories (Table 1): for example, values for Nauru, St. Pierre and Miquelon, Wallis and Futuna, Bhutan are calculated based on global average values. Data also shows that where global averages dominate calculations, this concerns very limited flight numbers (Table 1).

Table 1: Percentage of global average use in calculations

Top departure_country	Country	ga_count	total_count	share_within_country_ %	
1	NRU	Nauru	4	4	100
2	SPM	Saint Pierre and Miquelon	2	2	100
3	WLF	Wallis and Futuna	2	2	100
4	BTN	Bhutan	17	17	100
5	GRL	Greenland	95	100	95
6	YEM	Yemen	29	31	93.55
7	VEN	Venezuela, Bolivarian Republic of	141	156	90.38
8	AFG	Afghanistan	37	41	90.24
9	FRO	Faroe Islands	18	20	90
10	BLR	Belarus	38	43	88.37
11	LBY	Libyan Arab Jamahiriya	51	61	83.61
12	MHL	Marshall Islands	27	33	81.82
13	SOM	Somalia	54	67	80.6
14	VGB	Virgin Islands, British	8	10	80
15	TKM	Turkmenistan	41	52	78.85

Table 2 further illustrates that it is specific countries where global averages have been applied more often than in others: China, Russian Federation and India, for example, account for more than one third of cases, reflecting on limited reporting to ICAO, IATA and others. Even here, total case numbers are comparably small (considering total flight numbers), and do not affect the conclusions drawn in the paper.

Table 2: Countries with concentration of global average load factor use

Top departure_country	country_name	ga_count	total_count	share_of_global_pool_ %	Cum	
1	CHN	China	6294	23514	21.24	21.24
2	RUS	Russian Federation	2295	3308	7.75	28.99
3	IND	India	1889	3566	6.38	35.37
4	GBR	United Kingdom	1644	5637	5.55	40.92
5	TUR	Turkey	1139	4689	3.84	44.76
6	JPN	Japan	959	2505	3.24	48
7	ESP	Spain	928	5619	3.13	51.13
8	USA	United States	872	30485	2.94	54.07
9	MEX	Mexico	822	2602	2.77	56.84
10	CAN	Canada	822	3322	2.77	59.61
11	GRC	Greece	691	2493	2.33	61.94
12	FRA	France	622	4294	2.1	64.04
13	IDN	Indonesia	616	1452	2.08	66.12
14	ITA	Italy	539	4172	1.82	67.94
15	DEU	Germany	448	4952	1.51	69.45

For airlines, the top 15 (in terms of global average load factor application) were manually checked, tracking IATA airline codes back to the airlines (<https://www.iata.org/en/publications/directories/code-search>). The analysis confirms that these airlines do not report to any database, but even here, we conclude that this does not affect our results or conclusions. Some overlap occurs with Table 2 (e.g. Russian Federation – Aeroflot).

Table 3: Airlines not reporting (use of global average load factor)

Top	airline_iata	name	total_count	ga_count	share_ga_within_airline_%
1	3U	Sichuan Airlines	2235	2235	100
2	BY	TUI Airways Ltd dba Tui	1587	1587	100
3	6E	Interglobe Aviation Ltd. dba IndiGo	1550	1550	100
4	PC	Pegasus Airlines	1359	1359	100
5	LS	Jet2.com Limited	1106	1106	100
6	GS	Tianjin Airlines	814	814	100
7	SU	Aeroflot	655	655	100
8	JD	Beijing Capital Airlines Co. Ltd.	652	652	100
9	TB	TUI Airlines Belgium N.V dba TUI fly	549	549	100
10	HV	transavia.com/Transavia Airlines (Netherlands)	416	416	100
11	TO	Transavia France	411	411	100
12	DY	Norwegian Air Shuttle (Norway) Norwegian	376	376	100
13	WG	Wasaya Airways (Canada) Wasaya	332	332	100
14	UT	UTair	328	328	100
15	N4	LLC "NORD WIND"	325	325	100

Overall, we conclude that the potential error is largest where it has no relevance for our results and conclusions. All of this has been acknowledged in the updated limitations. We thus hope that the calculations confirm the robustness of the model and address the reviewer's concerns.

Response to Reviewers:

Large emission avoidance potential in improved commercial air transport efficiency (COMMSENV-25-1886)

Reviewer 2

Gössling et al. present an assessment of the CO₂ efficiency of global passenger air transport by analyzing over 27 million flights across more than 26,000 city pairs in 2023. The study reveals large variability in emissions per revenue passenger kilometer across different aircraft types, routes, airlines, and regions, and estimates the potential for emission reduction if operations were optimized to achieve best-practice efficiency levels.

I found the authors' approach interesting, as it highlights an important and underexplored opportunity for emission mitigation through operational improvements. However, several aspects need to be addressed before the paper is ready for publication.

1. The paper would benefit from a clearer discussion on the practical roadmap for implementing the proposed efficiency-enhancing strategies in support of sustainability goals. For instance, achieving a 95% load factor may be more feasible in the short term compared to fleet replacement with only the most efficient aircraft types, which is unlikely to be achievable in the short or even medium term. A more detailed discussion on the feasibility and timelines of these strategies is recommended.

We agree that a roadmap would be desirable. However, we believe that it is beyond the scope of this paper to engage with a full analysis of the political and business implications of our findings, as the current air transport system is driven by specific mindsets and political frameworks (continued growth, availability of subsidies). The purpose of our paper is to contribute an analysis of the theoretical bounds of the efficiency potential. To develop a roadmap would introduce subjectivity, and likely be criticized by industry as “unfeasible” either way. In this context, we also note that there is no evidence that any of the roadmap-like scenarios for aviation published in Nature journals has been implemented (e.g. Bergero et al. 2023; Dray et al. 2022). The reviewer is however correct that perspectives of “achievability” will vary, which we have now included in the paper in a generic discussion.

Bergero, C., Gosnell, G., Gielen, D., Kang, S., Bazilian, M., & Davis, S. J. (2023). Pathways to net-zero emissions from aviation. *Nature Sustainability*, 6(4), 404-414.

Dray, L., Schäfer, A. W., Grobler, C., Falter, C., Allroggen, F., Stettler, M. E., & Barrett, S. R. (2022). Cost and emissions pathways towards net-zero climate impacts in aviation. *Nature Climate Change*, 12(10), 956-962.

2. Building on the previous point, it would be valuable to discuss whether existing climate projections account for such improvements in air transport efficiency. If not, it is suggested that the authors discuss how the inclusion of these efficiency gains might change the existing projections (e.g., the well-known projection here: <https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/>, attributing 10% emission reduction to operations and infrastructure), especially about key milestone years (e.g., 2035, 2050)?

Yet, articles usually consider efficiency gains (e.g. Gössling and Humpe 2024). We have added a reference to Waypoint, noting again that there is no evidence of implementation of the measures discussed in Waypoint.

Gössling, S., & Humpe, A. (2024). Net-zero aviation: Transition barriers and radical climate policy design implications. *Science of the Total Environment*, 912, 169107.

3. While the focus is on CO₂, the analysis may also have implications for non-CO₂ climate effects (e.g., NO_x emissions-induced effects). As fuel consumption is directly tied to NO_x emissions, strategies that reduce fuel burn could also mitigate non-CO₂ climate effects (though it also has a dependency on the atmospheric background conditions). Such analysis could strengthen the paper by either quantifying potential NO_x climate impact reductions (e.g., in terms of climate metrics such as GWP) or including a discussion on this point.

We agree, and have noted implied non-CO₂ effects in the paper, but it is difficult to quantify these. Non-CO₂ emissions, on average, have a stronger climate effect than CO₂ itself. However, they only matter at high altitude, which causes them to affect short and long-haul flights differently, as short-haul flights will not fly above 9 km. For reasons of these complexities, the focus of this paper is thus on CO₂.

4. The statement that "the replacement of Jet A-1 with SAF ignores non-CO₂ components" may be somewhat misleading. SAF can reduce contrail warming by lowering soot particle emissions. Clarification of this point is necessary to ensure alignment with current scientific understanding.

Thank you - we have rephrased the sentence, which now reads:

“Efficiency gains have importance, because the replacement of Jet A1 with SAF does not eliminate non-CO₂ components, even though lower soot particle emissions can reduce effective radiative forcing (Märkl et al. 2024). Strategies minimizing fuel use are thus preferable, as they contribute to a reduction in CO₂ as well as non-CO₂ effects.”

5. A dedicated section on data collection and sources is recommended. In particular, the GitHub link referenced in the paper appears to be non-existent.

Data sources are presented in Methods, in the Efficiency model section. We use T100I, ICAO TFS, IATA WATS, and FlightGlobal data. If there is any remaining unclarity, please let us know. We apologize for the non-functional link. This was a place holder for the time being and should now work.

6. Do the authors expect the patterns illustrated in Figures 1 and 2 to remain similar over different years? A brief discussion on the generalizability of the findings would be beneficial in contextualizing the broader relevance of the results.

To answer the question, it would be necessary to recalculate the findings for different years. Given COVID-effects, such calculations with past data may have limited significance. It would thus be more appropriate to re-calculate in the future, when new data becomes available. The data presented is a snapshot of the situation in 2023, though it can generally be expected that there is some stability in the system in the absence of disruptions such as COVID: aircraft are in service for an average period of 25 years, for example, and airlines buy new aircraft continuously rather than replacing their entire fleet. Furthermore, flight distance, which is

stated to strongly impact efficiency, is unlikely to change significantly for larger airlines or airports annually - though load factors might, depending also on many complex economic factors, but save disruptions such as COVID, even load factors have been stable historically (Gössling and Humpe 2024). National politics also influence global aviation which will always impact the comparison of annual data. A discussion of the generalizability of the data is included in the new Limitations section.

Gössling, S., & Humpe, A. (2024). Net-zero aviation: Transition barriers and radical climate policy design implications. *Science of the Total Environment*, 912, 169107.

7. It is recommended to provide a more detailed discussion on the limitations of the current analysis, including the assumptions made and the challenges associated with implementing the proposed strategies.

We have now added a discussion on limitations, as well as the challenges associated with implementing a more efficient air transport system.

Reviewer 3

The authors use global datasets (ICAO, IATA, FlightGlobal, etc.) to systematically assess and compare the carbon efficiency of worldwide commercial flights in 2023. They explore operational differences across aircraft models, airlines, routes, and regions, and estimate the emission reduction potential from measures like fleet renewal, all-economy layouts, and higher load factors. While the study provides valuable insights and policy implications, several key issues—such as methodological assumptions and the feasibility of the proposed scenarios—still require further clarification.

1. The dataset used covers only 83% of total global RPK and 82% of passengers, which indicates a significant portion of missing data. Given that this missingness is likely to be non-random—for instance, systematically excluding certain countries, routes, or operational categories rather than generic charter flights—how does the study account for potential bias and ensure the reliability and representativeness of its results?

As a general disclaimer, there is no complete dataset for global aviation. This is a recurrent problem in air transport studies, even those using ADS-B data (Quadros et al. 2022). For example, Klenner et al. (2024) identified 36.2 million commercial flights in 2019, while Teoh et al. (2023) identified 40.2 million in that year. Yet, calculated emissions are higher in Klenner et al. (ibid.), at 920 TgCO₂, while Teoh et al. (ibid.) arrive at 893 TgCO₂. It is not entirely clear how differences can be explained, but Teoh et al. (ibid.) include military flights though Klenner et al. (ibid.) do not. Yet another study, Quadros et al. (2022), assesses “civil aviation”, reporting emissions of 937 TgCO₂ in 2019. The study does not reference the number of flights this refers to. Even though this is the highest emission estimate, Quadros et al. (2022) indicate that their calculated fuel consumption is 12.9% lower than worldwide jet kerosene consumption reported by the International Energy Agency for that year (compared to calculations based on OAG ADS-B data).

Given that Klenner (2024), Teoh et al. (2023), and Quadros et al. (2022) calculate emissions for 2019 – with different results -, these cannot be used for comparison with our dataset for 2023. As we have shown, the study however covers 83% of RPK, and 82% of passengers in comparison to ICAO data. As we have indicated, ICAO claims to cover 99% of air transport services reported for 2023. Our data should thus be reliable in the sense that 83% of RPK and 82% of passengers are accounted for.

We also suggest that our data is not biased, because we use official databases (such as IATA WATS). Consequently, our findings represent the air transport system included in these datasets, and findings are reliable for the system studied, but not representative of “aviation” (which also includes freight, private aviation, military flight, and helicopters and other specialized aircraft). We cannot account for details regarding the missing share of RPK (17%) and passengers (18%) in comparison to ICAO data, but there is no reason to assume that the missing data is systematically excluding “countries, routes, or operational categories”, or that our data use has repercussions for the reliability of the data. While we have discussed the system boundaries of our data - and hence cannot draw conclusions on the representativeness of our results for commercial air passenger transport -, we have now summarized uncertainties in a new limitations section. We have also added “commercial” to the title to be clear from the start that our paper is focused on commercial passenger air transport.

Klenner, J., Muri, H., & Strømman, A. H. (2024). Domestic and international aviation emission inventories for the UNFCCC parties. *Environmental Research Letters*, 19(5), 054019.

Quadros, F. D., Snellen, M., Sun, J. & Dedoussi, I. C. Global civil aviation emissions estimates for 2017–2020 using ADS-B data. *J. Aircr.* 59, 1394–1405 (2022).

Teoh, R., Engberg, Z., Shapiro, M., Dray, L. & Stettler, M. E. The high-resolution Global Aviation Emissions Inventory based on ADS-B (GAIA) for 2019–2021. *Atmos. Chem. Phys.* 24, 725–744 (2024).

2. Does the manuscript use actual seat configuration data for each flight? Even for the same aircraft type, seat layouts can vary significantly between airlines.

Yes, the OAG flight schedule contains the actual cabin layout for each individual flight.

3. The scenarios based on the most efficient aircraft, all-economy layouts, and a 95% load factor seem highly idealized and difficult to achieve in practice, considering cost factors, the need for service differentiation between LCCs and FSCs, and limited demand on certain routes.

This is entirely correct. We assess the theoretical maximum efficiency in the air transport system characterized by the data. In the current air transport system, it is likely only possible to increase efficiencies gradually - without an expectation of ever achieving maximum efficiency, which indeed would be more difficult to achieve for FSCs than LCCs. Knowledge of the theoretical maximum efficiency however makes it possible for airlines and policymakers to implement measures that move the system towards greater efficiency. How this is to be achieved in practice, and to which limits, is a question that we do not pursue in more detail in this paper.

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flown distance may differ substantially depending on the country or specific route, as a result of varying airspace structures and operational conditions.

We do agree, but this is the official measure used in international civil aviation. It seems more appropriate to use the established industry norms than to devise our own that the industry would then criticize. We have however added this concern to the limitations section. Perhaps to add, also with a view to the following comment, our calculations are focused on yearly averages for citypairs, airlines, and aircraft. Hence, daily changes in flight distance because of weather conditions or other factors are averaged out.

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“The resulting per-passenger emission intensity enables comparisons of flight efficiency. Figure 8 illustrates the inherent dependence of emission intensity on flight distance, with longer flights generally exhibiting lower emission intensities. This is because takeoff and ascent to cruising altitude - the most fuel-intensive phase of a flight - account for a larger proportion of total fuel burn on short-haul routes.”

7.The use of formula screenshots in the Word manuscript is not appropriate. In summary, data gaps and crude calculations in the current manuscript make it difficult to ensure the accuracy of the results. Improving the precision of calculations is strongly recommended.

We apologize, this is entirely correct, and a result of all of us working in an online google document not allowing for formula inclusion. All formulas are now included. We have also reconsidered these to address the precision concern.

Response to Reviewers (COMMSENV-25-1886A):

Large emission avoidance potential in improved commercial air transport efficiency

Reviewer #2 (Remarks to the Author):

Gössling et al. have sufficiently addressed my concerns and incorporated discussions on the raised points. I have no further comments and recommend acceptance of the manuscript.

Thank you

Reviewer #3 (Remarks to the Author):

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Thank you for this observation and the concern expressed about load factor accuracy. To address the question, we assessed load factor granularity, calculating the induced error in the comparison of global averages and T100I data. The revised Methods now reads:

“To factor these aspects into the calculation of emissions per RPK, an efficiency model is used that considers distance, aircraft type, and payload (passenger and cargo weight). 2023 data for the efficiency model is derived from:

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For each individual flight, the highest level of load factor is sought, following a fallback cascade across the data sources. When IATA WATS is established as the best data source, the corresponding value for either domestic or international flights is used. As a last fallback, a global load factor over all airlines is calculated for three distance categories: short-haul (≤ 1500 km), medium-haul (1500 - 3500 km) and long haul (>3500 km). This load factor is used when no other load factor (level 1-3) can be found.

The induced error can be calculated for using global means instead of level 3 values. When bootstrapping 100,000 samples, the per-flight absolute error mean is 0.0406, and the median is 0.0145. The bootstrapped 95% CI for the absolute error mean is [0.0389, 0.0423]. This corresponds to a relative error of 5.38% with a 95% CI of [5.15%, 5.62%]. Notably, this error affects 20.4% of the load factor, as a higher-level granularity for load factors is available for 79.6% of flights.”

The limited error in calculations is also illustrated in Figure 5 and Figure 8 in the manuscript. Figure 5 shows CO₂ intensity by load factor and airline, highlighting a global average load factor of around 0.8. Figure 5 also shows, however, that the largest 30 airlines in the world are not concentrated around 0.8, and thus not or only marginally affected by the use of a global average for calculations where no level 1 to 3 data is available. Similarly, the artifact caused by the average load factor around 0.8 is also visible in Figure 8 and reveals that it is most relevant for short distances below 500 km (brown colour scheme).

To further assess whether the average error is large for specific countries or airlines, we calculated the average error for individual flights (global average in comparison to level 3), finding that it can be large, with a 95% CI of [-0.1473, 0.3812] (Figure 1).

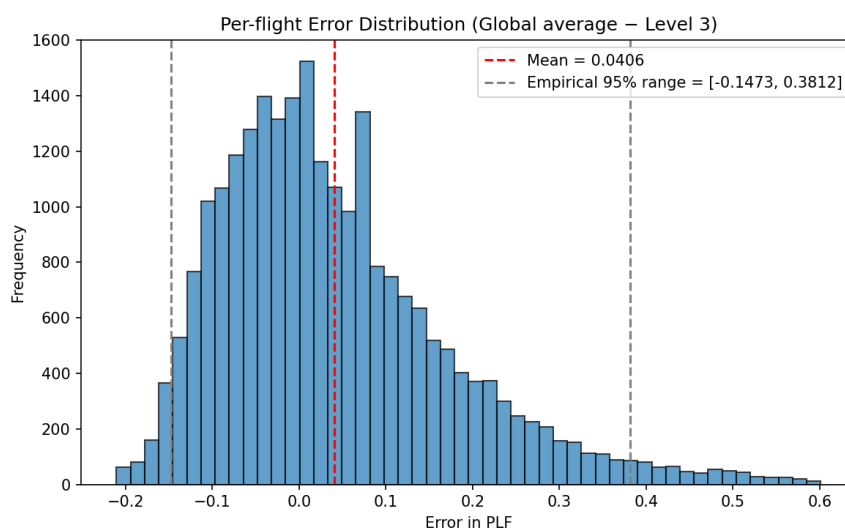


Figure 1: Error distribution, individual flights

Further detailed analysis however shows that the use of global averages has no effect on result presentation or the conclusions drawn in the paper. Countries most affected by the use of a global average load factor represent small, remote, or politically isolated territories (Table 1): for example, values for Nauru, St. Pierre and Miquelon, Wallis and Futuna, Bhutan are calculated based on global

average values. Data also shows that where global averages dominate calculations, this concerns very limited flight numbers (Table 1).

Table 1: Percentage of global average use in calculations

Top	departure_country	Country	ga_count	total_count	share_within_country_ %
1	NRU	Nauru	4	4	100
2	SPM	Saint Pierre and Miquelon	2	2	100
3	WLF	Wallis and Futuna	2	2	100
4	BTN	Bhutan	17	17	100
5	GRL	Greenland	95	100	95
6	YEM	Yemen	29	31	93.55
7	VEN	Venezuela, Bolivarian Republic of	141	156	90.38
8	AFG	Afghanistan	37	41	90.24
9	FRO	Faroe Islands	18	20	90
10	BLR	Belarus	38	43	88.37
11	LBY	Libyan Arab Jamahiriya	51	61	83.61
12	MHL	Marshall Islands	27	33	81.82
13	SOM	Somalia	54	67	80.6
14	VGB	Virgin Islands, British	8	10	80
15	TKM	Turkmenistan	41	52	78.85

Table 2 further illustrates that it is specific countries where global averages have been applied more often than in others: China, Russian Federation and India, for example, account for more than one third of cases, reflecting on limited reporting to ICAO, IATA and others. Even here, total case numbers are comparably small (considering total flight numbers), and do not affect the conclusions drawn in the paper.

Table 2: Countries with concentration of global average load factor use

Top	departure_country	country_name	ga_count	total_count	share_of_global_pool_ %	Cum
1	CHN	China	6294	23514	21.24	21.24
2	RUS	Russian Federation	2295	3308	7.75	28.99
3	IND	India	1889	3566	6.38	35.37
4	GBR	United Kingdom	1644	5637	5.55	40.92
5	TUR	Turkey	1139	4689	3.84	44.76
6	JPN	Japan	959	2505	3.24	48
7	ESP	Spain	928	5619	3.13	51.13
8	USA	United States	872	30485	2.94	54.07
9	MEX	Mexico	822	2602	2.77	56.84
10	CAN	Canada	822	3322	2.77	59.61
11	GRC	Greece	691	2493	2.33	61.94
12	FRA	France	622	4294	2.1	64.04
13	IDN	Indonesia	616	1452	2.08	66.12
14	ITA	Italy	539	4172	1.82	67.94
15	DEU	Germany	448	4952	1.51	69.45

For airlines, the top 15 (in terms of global average load factor application) were manually checked, tracking IATA airline codes back to the airlines (<https://www.iata.org/en/publications/directories/code-search>). The analysis confirms that these airlines do not report to any database, but even here, we conclude that this does not affect our results or conclusions. Some overlap occurs with Table 2 (e.g. Russian Federation – Aeroflot).

Table 3: Airlines not reporting (use of global average load factor)

Top	airline_iata	name	total_count	ga_count	share_ga_within_airline_%
1	3U	Sichuan Airlines	2235	2235	100
2	BY	TUI Airways Ltd dba Tui	1587	1587	100
3	6E	Interglobe Aviation Ltd. dba IndiGo	1550	1550	100
4	PC	Pegasus Airlines	1359	1359	100
5	LS	Jet2.com Limited	1106	1106	100
6	GS	Tianjin Airlines	814	814	100
7	SU	Aeroflot	655	655	100
8	JD	Beijing Capital Airlines Co. Ltd.	652	652	100
9	TB	TUI Airlines Belgium N.V dba TUI fly	549	549	100
10	HV	transavia.com/Transavia Airlines (Netherlan	416	416	100
11	TO	Transavia France	411	411	100
12	DY	Norwegian Air Shut le (Norway) Nor Shut le	376	376	100
13	WG	Wasaya Airways (Canada) Wasaya	332	332	100
14	UT	UTair	328	328	100
15	N4	LLC "NORD WIND"	325	325	100

Overall, we conclude that the potential error is largest where it has no relevance for our results and conclusions. All of this has been acknowledged in the updated limitations. We thus hope that the calculations confirm the robustness of the model and address the reviewer's concerns.

Response to Reviewers (COMMSENV-25-1886B):

REVIEWERS' COMMENTS:

Reviewer #3 (Remarks to the Author):

The authors have addressed my concerns.