nature portfolio

Peer Review File

Fuel shifts reduce most of the greenhouse gas emissions from transportation in the United States

Corresponding Author: Professor Jason Quinn

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

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Quinn,

Your manuscript titled "Evaluating present and future climate impacts of transportation modes" has now been seen by 3 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.

In order to meet the editorial threshold the authors must provide novel and well-supported insight into the greenhouse gas emission reduction from modified travel behavior including the use of electric scooters, rails, and buses in the United States. Additionally, the authors should meticulously delineate their methodology in detail so that independent researchers can replicate your study, provide sensitivity and uncertainty analysis, and validate and compare your findings with existing literature. Moreover, the authors must consider widening the scope of the analysis to account for fleet-level in their analysis provide in-depth discussions of the approach and findings, and demonstrate that the author's claims are robustly supported.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

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

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers’ comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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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,

Pallav Purohit, PhD
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Martina Grecequet, PhD
Associate Editor
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@CommsEarth

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This is an important topic but there have been many studies comparing the emissions and energy consumptions per mile among transportation mode. I had hard time to understand the contribution of this paper. Plus, I personally do not agree to include the dietary GHG emissions of walking and traditional bicycles. Operating electric bikes, scooters and even vehicles and locomotives require human effort as well. Plus, it's debatable whether the increased dietary GHG is only due to human effort for propulsion.

Reviewer #2 (Remarks to the Author):

The paper is of relevance and interest, and mostly well written.

I have a few concerns.

The title must include mentioning of the US here. Results from other parts of the world are very different.

The abstract is quite unclear.

"This study shows that modifying travel behavior, including using electric scooters and increasing ridership for rail and buses, can yield more immediate reductions in GHG emissions than transportation electrification."

--> What does immediate mean? Does it include a consideration that busses are not available in most parts of the US, and that escooters or bikes are too dangerous on most roads? I tend to agree with the sentence, but I think it would be important to voice the constraints on this statements, and also consider what to do (safe infrastructures, TOD, etc.) in the discussion.

"However, electrified transport can achieve half the emissions of petroleum-fueled options in 2023 and a sixth in 2050."

--> I don't understand this sentence. We have now 2024. So how can elec trans reduce emissions by half in 2023?

" Battery systems in electrified transport account for up to a fifth of lifetime emissions in 2023, increasing to half in 2050 when fuel emissions are greatly reduced."

--> does it mean "fifth of lifetime emissions of EVs?

"This study suggests that the greatest emissions reductions can be achieved through adopting technologies energized by decarbonized electricity and changing travel behavior."

--> Before in the abstract you emphasize micromobility. Now it is overall electrified transport again. Inconsistent messaging.

The results and figures point to the importance of occupancy. But then in the discussion this is lost. I would suggest to take it up in the discussion, and possibly also in the abstract.

The walking numbers are staggering. However, it is methodologically problematic to allocate dietary issues to mode choice. That is even more relevant as walking is one of the main strategies to reduce non-communicable diseases in the US, a major public health policy, that is very important. Figures of your paper could be taken out of context (not the authors' intention) to problematize active travel. Consider two remedies: change the visuals from strong to weak coloring (low intensity) of the dietary part of walking and cycling. Also clarify in the legend that this part is actually dietary issues and can be adressed by dietary change. Also then reflect the issue of dietary change in the text.

Discuss the results in the context of similar studies, e.g., this one: https://il.boell.org/sites/default/files/2021-03/Felix Creutzig - Making Smart Mobility Sustainable.pdf

Results are similar but not identical (based on ITF numbers in the case above) and it would be helpful to clarify differences and similarities.

Last but not least, consider picking up Ch10 of the IPCC 2022 report on climate solutions, where I believe micromobility does play a less pronounced role compared to fuel shift. That could serve as a motivation for your manuscript. Other publications also provide context (e.g., https://www.tandfonline.com/doi/pdf/10.1080/01441647.2015.1079277?casa_token=B2OgPGasjb4AAAAA:OXloClSbGwMFifFkYeowW0VHAWivcbT7if240cWkH_r-JrDldedVo5kGy6aTi-myzcEB10xLJ84UQaM, and https://d1wqtxts1xzle7.cloudfront.net/100047018/annurev-environ-031913-100450-libre.pdf?1679245617=&response-content-disposition=inline;+filename=Energy_for_Transport.pdf&Expires=1712413658&Signature=WTWQw~vTY0Xs~LHQevkBZs~yQlMOuBWx95QcNJervWDsM7gzdkABNxNb~OqB9Mmm2iko1AlZlrCzft2-g5oxMw2NOgMFDpjtEsV0eB1PAoSLcPlHW~--vldKM2kcX8PztMaSRRuUGEdUPvD0M49XOk7RK-bVDuu46OnSJyxeHUYTmyHGYJpna-DurWfh-lwdm8w8riRbcXOFs9-nJwmgmXulMhlyzLtncAbd1EXiAFiqI-5SfQruu1qUuvrpG8xhhHyiW-yaZpU-oZ05A8ldY0Ea1fnlt~srlRM2vldeXlDj4rGBuh62DUO1Q5XQE-p1Nv-6WxQLJMuTsB2b~BZhkg__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA).

Reviewer #3 (Remarks to the Author):

Currently, the study lacks the types of checks one would expect from a high-quality work relying on life cycle assessment, namely sensitivity and uncertainty analyses, complemented by validation against literature. Any error or approximation in a critical input parameter can change the study's conclusion. Hence, special attention needs to be paid to ensure critical input values are robust and correct, and, very importantly, the reader should be able to judge this by presenting such inputs in a clear and transparent manner.

Additionally, this study feels incomplete. It informs on the potential GHG emission reductions by shifting towards collective means of transport and increasing their occupancy rate, but the reader never really gets to see the “big picture”, i.e., the fleet-level GHG emissions reduction potential.

In my opinion, the study stops a step too early, i.e., the comparison of GHG emissions per passenger-kilometer. I believe this substantially reduces the added value of the work because while the study tells us that some modes of transportation are much more efficient than others, this is not new. Studies (e.g., https://doi.org/10.1016/j.jclepro.2020.122898, https://doi.org/10.1007/978-3-319-58538-3_192-1, https://www.mdpi.com/2071-1050/12/18/7548, are a few ones I could find in a few minutes), databases (e.g., ecoinvent) and tools (e.g., mobitool, GREET) already give us the lifecycle-based GHG emission factors across transportation, even though they may not have a strictly similar technological, temporal or geographical scope. Existing studies have not told us yet whether, at scale, those lifecycle-based emission reductions are important or not (or even feasible), which is something your study currently falls short of.

Hence, I regret to say that, while quite informative, the scope needs to be widened to the fleet level (not simply multiplying the GHG emission factors by the demand, but also accounting for realistic modal shifts given trip distances, infrastructure capacity, etc.). Without this, I do not see the novelty of this work (at least, not the standards of a Nature Portfolio journal).

I have some additional and more detailed remarks below.

Title: the study has a USA scope of analysis. This should be reflected in the title.

Abstract: “This study suggests that the greatest emissions reductions can be achieved through adopting technologies energized by decarbonized electricity and changing travel behavior.” This seems to be presented as the study's main “take-away” message. But this is not really teaching us anything new about the challenge of decarbonizing the transport sector. Electrifying transport, coupled with low-carbon electricity and an increased occupancy rate, have been known levers to reduce GHG emissions from the past decade or so.

Main

p.1 l.26: I am not convinced the goal is to reduce the total passenger-kilometers. Instead, the goal is probably to reduce the number of vehicle-kilometers (and favor the most efficient vehicles) while keeping the same level of service (i.e., passenger kilometers).

Ref. 15 is not a peer-reviewed academic work, but a white report from the ICCT, subjected to an internal and partly external (but non-anonymous) review. I strongly suggest favouring single-blind peer-reviewed academic sources. Additionally, the buses and other heavy-duty vehicles modelled in this ICCT report are specific in mass and fuel consumption to the EU market, which differs from your geographical scope. At the same time, you indicate the use of the GREET model for buses, so please be more specific on the role of Ref. 15.

p.3 l.3: you cannot draw conclusions on the environmental impacts of a system solely based on its GHG emissions. Please reformulate. Furthermore, as you rightly point out in the Methods section, emissions related to active modes of transport are sensitive to the diet. You should at least mention the type of diet considered to provide the additional effort needed to move the vehicle (e.g., US-average, protein-rich, meat-based, etc.)

Figure 2 gives the impression of robust and certain numbers. GHG emissions from collective means of transport are very sensitive to use-related parameters, such as lifetime and occupancy rate. Active means of transport are sensitive to the food diet. Electrified means of transport are sensitive to battery chemistry, capacity and carbon intensity of the electricity. The reader would expect a more sophisticated figure, showing all these nuances, uncertainty and effects of modelling choices. This is especially the case when it currently shows that collective and active means of transport (i.e., bus and walking) emit more GHG than passenger cars.

Also, I struggle with the fact of comparing walking and driving without nuances. While one may substitute the other, this is only really the case in urban contexts, for very short distances. Yet, you model your vehicles using national statistics and average traffic situations (including fuel consumption). This is incorrect in my opinion. The transportation modes you present only compete on certain market segments, such as urban mobility. Hence, to keep this comparison valid, I suggest redefining the scope of the analysis of urban mobility options and modifying the vehicles' specifications accordingly (and the manuscript's title, too).

Additionally, electric scooters are known to have a relatively short lifetime. It is surprising to see them having lower GHG emissions than bicycles. One would expect higher GHG emissions from the scooter itself (because it is normalized by a lower lifetime), while lower emissions from electricity use. You refer to Ref.16 for a lifetime of 10,000 km, but Ref. 16 uses a lifetime of 2,117 km for electric scooters. Why such a difference?
The lifetime value of bicycles is from Ref. 35. In this document, they calculate the lifecycle-based GHG emission per PKT and find a total of 21 gCO_2e. This contrasts quite a bit with your number (107 gCO_2e). Can this really be explained by a difference in diet? It is necessary that you validate your per PKT numbers against the literature to assert the robustness of your results.

I believe that if I continued searching for other vehicles, I'd keep finding such differences between assumptions and input values used in the literature and those you used. Hence, it is important you do this work yourself and justify your choices and their effects in a transparent manner.

In summary, and for the sake of clarity, I strongly suggest:
1. Adding a table in the Methods sections, showing all the important parameters for all vehicles (lifetime in kilometers and years, occupancy, fuel economy/food intake, mass, battery capacity, etc.), and the uncertainty range and source. Also, indicate clearly the GHG emission factor per unit of fuel/food/electricity (e.g., gCO_2e/MJ) and those for battery manufacture (kg CO_2e/kWh of battery capacity). While this information is mainly present already, it is scattered and hard to compare across vehicles. Your study will benefit a lot from such clarity and transparency.
2. Adding some results validation, comparing your input values and emission factors and results with those of the literature. Hopefully, this will help you detect inconsistencies.
3. The first two points should somehow be reflected in Figure 2 and, ultimately, Figures 3 and 4, showing the variability in results due to uncertainty and modelling choices.

Figure 3: the current and maximum occupancy values should be included in this figure.

Supplementary materials, Table 2. The battery GHG emission per PKT for buses is 4.8 gCO_2. Roughly, this represents (0.0048 kg CO_2e * 800'000 km * 7.6 pass/vehicle)/200 kWh = 144 kg CO_2e/kWh. Is this really representative of the carbon footprint of batteries? This type of information should become apparent and be validated against the rest of the literature.

Supplementary materials, Table 3. Some reductions in terms of GHG emissions are striking, to say the least. For example, for intercity rail, it goes from 56 gCO_2/PKT to 0.26 (effectively, a 215-reduction factor). Is this really correct? If the electricity is that much greener in the future, does it really include lifecycle emissions (i.e., emissions from building wind turbines, solar PV, etc.), or are those only direct emissions from the power plants? Please add in the parameters table I asked you to insert the GHG emission intensity per kWh (or per MJ).

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Version 1:

Decision Letter:

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Dear Professor Quinn,

Your manuscript titled "Evaluating present and future climate impacts of transportation modes in the United States" has now been seen by our reviewers 1 and 3. Please note that the reviewer 2 was unable to provide feedback. All reviewers' 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 revise your paper one last time to address the remaining concerns of our reviewers. In particular, for publication in Communications Earth & Environment, we request that you highlight novelty and contribution to existing literature. At the same time, we ask that you 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,

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Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-7265-6960

Martina Grecequet, PhD
Senior Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thanks for addressing my comments. I have no further questions.

Reviewer #3 (Remarks to the Author):

While I do not necessarily agree with all the assumptions and values used in this study, the authors have made the necessary efforts to present them transparently to the readers. Also, adding the Monte Carlo and sensitivity analyses adds previously missing information. This effort is very welcome.

Hence, I think the study is comprehensive and of good quality.

However, I still fail to see the novelty of the work. If we summarize the findings:

- Battery systems's relative carbon footprint will increase by 2050 as the energy system decarbonizes.
- Shifting away from light-duty vehicles can achieve near-term GHG reductions.
- And the greatest emissions reduction is achieved by switching to decarbonized power.

I may lack perspective on this topic, but I assume most readers have known about this already.

Reviewer #1 (Remarks to the Author):

The authors appreciate the reviewer's valuable feedback. We have carefully addressed each comment, resulting in significant improvements to the manuscript through the revision process.

Comment 1.1

This is an important topic but there have been many studies comparing the emissions and energy consumptions per mile among transportation mode. I had hard time to understand the contribution of this paper.

Thank you for identifying that the contributions of the paper were not clearly stated and could be enhanced. To enhance the contributions of the work we have added a Monte Carlo analysis and fleet transition result. We have also added text to clarify the contributions of the work. Please find the last two paragraphs of the Introduction below, with the contributions highlighted in yellow.

"Several studies have assessed the GHG emissions associated with various modes of inland transportation. Noussan et al. (2022) reviewed and compared the GHG emissions factors of passenger transportation modes, finding that bicycles and rail had the lowest GHG emissions, while cars had the highest[5]. This study surveyed available literature from specific locales, capturing the mean rather than the United States average[5]. Creutzig (2021) compared the GHG emissions of active transportation modes to buses, rail, and cars in Germany and Israel, discovering that shared electric scooters had higher emissions than buses and rail but lower emissions than cars with one occupant[6]. Moreover, Creutzig (2021) found private bicycles and electric scooters to have the lowest emissions among the modes considered, though these results do not use United States parameters[6]. For instance, Figueroa et al. (2014) noted that the energy intensity of buses per PKT in the United States is much higher than the rest of the world due to low ridership, highlighting the importance of evaluating GHG emissions specific to United States parameters[7]. These studies have been limited in scale and have not deliberately calculated the United States average, which is needed to compare and contextualize GHG emissions reductions possible through mode shifts and technology advancements on an impactful nationwide scale to inform transportation and energy sector policy.

This study aims to address these critical issues by leveraging data on the United States average passenger load factors, fuel economies across vehicle ages, and the technological composition of various inland transportation modes. It employs a robust methodology, including consistent assumptions for mode comparisons, Monte Carlo simulations to capture uncertainty, and the inclusion of dietary emissions associated with each mode. By comprehensively assessing the attributional life cycle emissions associated with each mode, this research provides valuable insights into GHG emissions in the United States transportation sector, providing a transparent breakdown of emissions for each mode, including both current conditions and potential future advancements. The assessment involves the determination of total PKT and GHG emissions for each transportation mode based on their current technological profiles. Moreover, the study explores current technology models and high ridership scenarios to identify technologies capable of reducing emissions. It also projects GHG emissions for 2050, assuming a decarbonized electricity grid, and highlights each technology's potential for emissions reduction. Finally, the research contextualizes the results in terms of emissions reductions achievable through urban mode shifts and a transition to technologies using decarbonized electricity. The study finds that while shifting to public transportation and active modes can reduce GHG emissions, advancements in technology and electrification have a greater potential for reducing emissions by up to 85% by 2050. The results indicate that the majority of GHG emissions reductions can be achieved through fuel shifts alone, with mode shifts providing modest reductions in the near-term and minimal reductions in the long-term."

Comment 1.2

Plus, I personally do not agree to include the dietary GHG emissions of walking and traditional bicycles. Operating electric bikes, scooters and even vehicles and locomotives require human effort as well. Plus, it's debatable whether the increased dietary GHG is only due to human effort for propulsion.

Thank you for noting concerns over the inclusion of dietary GHG emissions and the inconsistency among modes. We have added dietary emissions for each transportation mode and delineated it in a light color at the tail end in Figs. 2-4 and presented the total separately in Fig. 5 to clearly show the emissions rates without the inclusion of dietary emissions. Further, we have added text in each of the captions highlighting that the emissions from dietary intake are due to dietary habits. Finally, we have added text to the Discussion section highlighting your concern of compensatory dietary emissions. Please find these updates to the manuscript below.

Dietary Emissions in Discussion

"Similarly, sustainable diets have the potential to both lower dietary GHG emissions and provide health benefits[31]. Emissions from dietary choices are highly variable, influenced by individual diets and geographical factors[16,22,27,31]. The compensatory dietary intake associated with active modes of transportation remains uncertain and varies widely[5], with one study suggesting a range between 19% and 96%[16]. However, as an attributional life cycle assessment, this study fully considers the GHG intensity of the additional energy required for human effort for each transportation mode."

Updated Results:

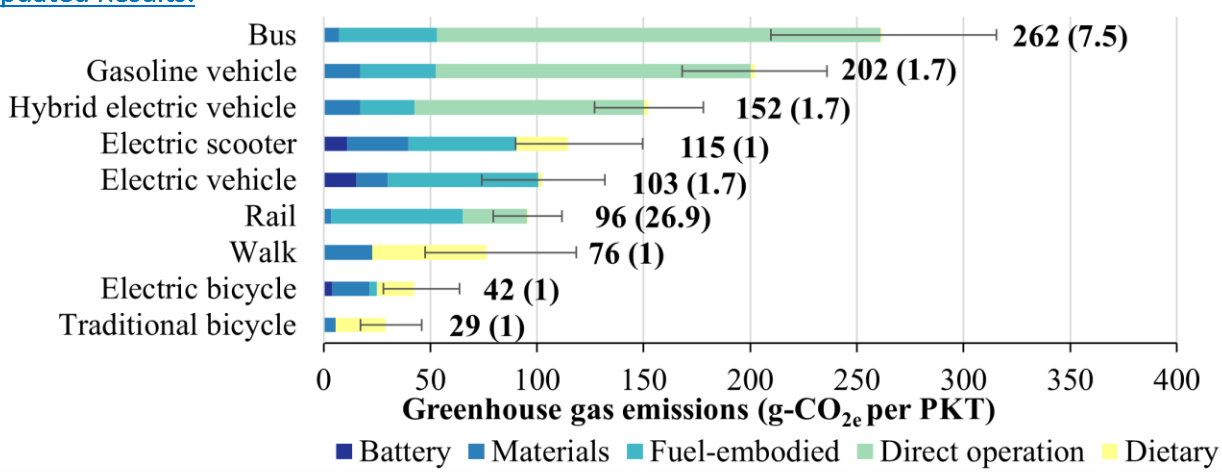

Fig. 2. Average greenhouse gas emissions of transportation mode compositions in 2023. The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The average ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); passenger kilometer traveled (PKT).

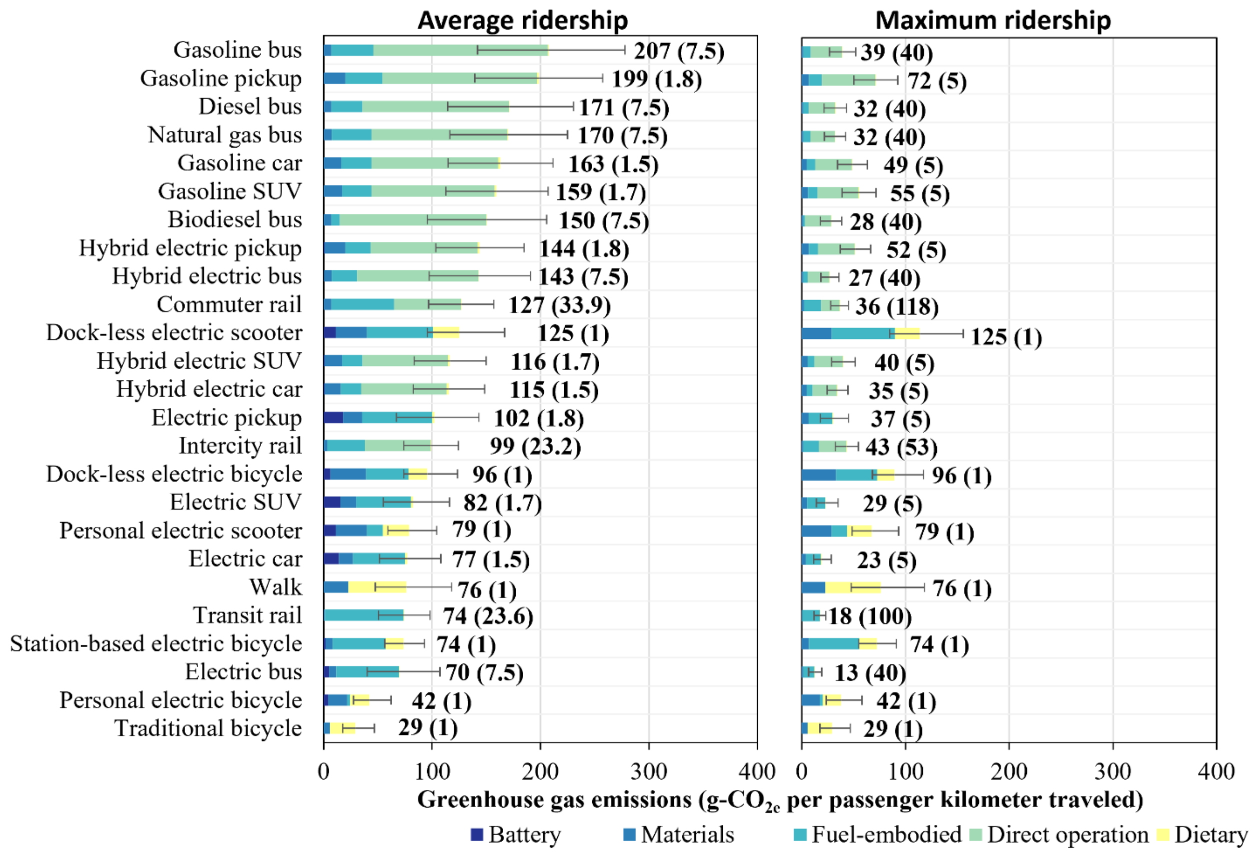

Fig. 3. Greenhouse gas emissions of 2023 transportation technology models. Results are presented for average ridership (left) and maximum ridership (right). The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); sport utility vehicle (SUV).

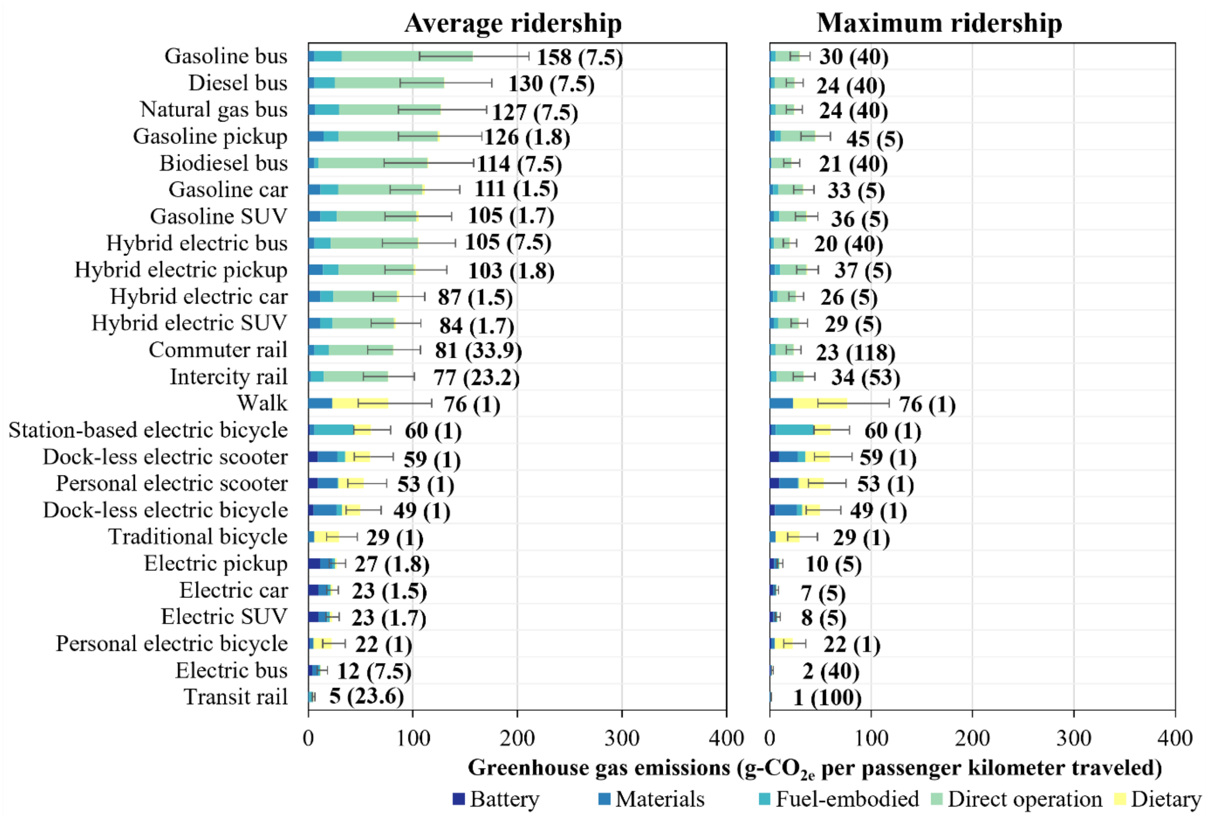

Fig. 4. Greenhouse gas emissions of 2050 transportation technology models with a decarbonized electricity grid. Results are presented for average ridership (left) and maximum ridership (right). The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); sport utility vehicle (SUV).

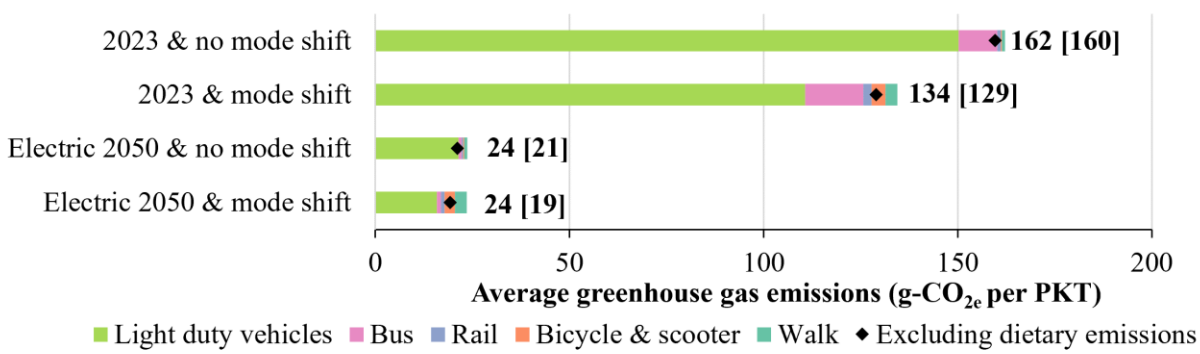

Fig. 5. Average urban greenhouse gas emissions from various transportation scenarios, including 2023 technology without mode shift, 2023 technology with mode shift, 2050 electric technology without mode shift, and 2050 electric technology with mode shift. The emissions are expressed as grams of Carbon Dioxide equivalent per passenger-kilometer traveled (g-CO_{2e} per PKT). Values within brackets exclude dietary emissions.

Reviewer #2 (Remarks to the Author):

The authors are grateful to the reviewer for support and the constructive comments. We have diligently worked to address all of the comments and feel the manuscript has been improved through the revision process.

Comment 2.1

The paper is of relevance and interest, and mostly well written.
I have a few concerns.

The title must include mentioning of the US here. Results from other parts of the world are very different.
Thank you for the recognizing the need for this distinction. Please see the updated title below:
"Evaluating present and future climate impacts of transportation modes in the United States"

Comment 2.2

The abstract is quite unclear.
Thank you for identifying that the abstract was unclear and needed to be rewritten. Please find the updated abstract below:

"Decarbonizing the United States transportation sector has emerged as a critical objective to combat climate change due to its high greenhouse gas (GHG) emissions, largely from light-duty vehicles. This study assesses the breakdown of life cycle emissions of various transportation options under average and maximum ridership scenarios and quantifies emissions reductions through mode shifts and technology advancements. Electrified transportation achieves half the GHG emissions of petroleum-fueled options as of 2023, with projections indicating a reduction to one-fifth by 2050. Battery systems contribute up to one-fifth of lifetime emissions of electric vehicles and buses as of 2023, and this share is estimated to increase to half by 2050 as electric fuel emissions are greatly reduced with decarbonized electricity. The study concludes that shifting away from light-duty vehicles can achieve near-term GHG reductions, but these reductions are minimal in the long term when combined with transportation electrification powered by decarbonized electricity."

Comment 2.3

"This study shows that modifying travel behavior, including using electric scooters and increasing ridership for rail and buses, can yield more immediate reductions in GHG emissions than transportation electrification."
--> What does immediate mean?
Thank you for identifying that "immediate" is not the appropriate word. We have replaced "immediate" with "near-term" throughout the manuscript. This sentence in the abstract has been removed in the revised version.

Comment 2.4

Does it include a consideration that busses are not available in most parts of the US, and that escooters or bikes are too dangerous on most roads? I tend to agree with the sentence, but I think it would be important to voice the constraints on this statements, and also consider what to do

(safe infrastructures, TOD, etc.) in the discussion.
Thank you for suggesting the addition of discussions related to safety and the limited usability of certain transportation modes. We have incorporated the following sentences into the Discussion section:

"Shifts in transportation modes away from light-duty vehicles are largely constrained by locational factors, with the adoption of public transportation and active modes primarily limited to urban areas[25,34]. Moreover, public transportation has limited coverage across the United States[35] and, if expanded, would require adequate ridership to achieve GHG emissions reductions relative to light-duty vehicles (Fig. 3)."

"Active transportation also requires safe infrastructure, which may need to be expanded, and is best suited for short trip distances, limiting its usage[34]."

Comment 2.5

"However, electrified transport can achieve half the emissions of petroleum-fueled options in 2023 and a sixth in 2050."
--> I don't understand this sentence. We have now 2024. So how can elec trans reduce emissions by half in 2023?
Thank you for noting that this sentence was unclear. Please find the reworded sentence below:

"Electrified transportation achieves half the GHG emissions of petroleum-fueled options as of 2023, with projections indicating a reduction to one-fifth by 2050."

Comment 2.6

" Battery systems in electrified transport account for up to a fifth of lifetime emissions in 2023, increasing to half in 2050 when fuel emissions are greatly reduced."

--> does it mean "fifth of lifetime emissions of EVs?

Thank you for identifying that this sentence required clarification. Please find the updated sentence below:

"Battery systems contribute up to one-fifth of lifetime emissions of electric vehicles and buses as of 2023, and this share is estimated to increase to half by 2050 as electric fuel emissions are greatly reduced with decarbonized electricity."

Comment 2.7

"This study suggests that the greatest emissions reductions can be achieved through adopting technologies energized by decarbonized electricity and changing travel behavior."
--> Before in the abstract you emphasize micromobility. Now it is overall electrified transport again. Inconsistent messaging.
Thank you for pointing out the inconsistency in the messaging of the paper. We have thoroughly reviewed the manuscript and emphasized the emissions reductions achieved through electrified transportation. Please find the main takeaway, as stated in the abstract below:

"The study concludes that shifting away from light-duty vehicles can achieve near-term GHG reductions, but these reductions are minimal in the long term when combined with transportation electrification powered by decarbonized electricity."

Comment 2.8

The results and figures point to the importance of occupancy. But then in the discussion this is lost. I would suggest to take it up in the discussion, and possibly also in the abstract.
Thank you for noting the importance of adding occupancy to the discussion. Please find the updated paragraph in the discussion section below, with the specific parts discussing occupancy highlighted:

"The decarbonization of the United States transportation sector necessitates substantial shifts in transportation behaviors and technological preferences. Despite buses having relatively high emissions due to low ridership, public transportation plays a vital role in ensuring mobility access, particularly for disadvantaged populations[33]. In the near-term, enhancing the ridership of public transportation modes like buses and rail not only curtails light-duty vehicle travel and its associated GHG emissions but also leads to GHG emissions reductions (Fig. 5) and financial savings per PKT for these modes. Shifts in transportation modes away from light-duty vehicles are largely constrained by locational factors, with the adoption of public transportation and active modes primarily limited to urban areas[25,34]. Moreover, public transportation has limited coverage across the United States[35] and, if expanded, would require adequate ridership to achieve GHG emissions reductions relative to light-duty vehicles (Fig. 3)."

Comment 2.9

The walking numbers are staggering. However, it is methodologically problematic to allocate dietary issues to mode choice. That is even more relevant as walking is one of the main strategies to reduce non-communicable diseases in the US, a major public health policy, that is very important. Figures of your paper could be taken out of context (not the authors' intention) to problematize active travel. Consider two remedies: change the visuals from strong to weak coloring (low intensity) of the dietary part of walking and cycling. Also clarify in the legend that this part is actually dietary issues and can be adressed by dietary change. Also then reflect the issue of dietary change in the text.
Thank you for the suggestion. Please note that we have revised the assumed value for daily dietary emissions by using a different source, Bassi et al. (2022), which provides dietary GHG emissions specific to the United States and accounts for recent reductions in dietary GHG emissions.

Following your recommendation, we have delineated the dietary emissions at the end of each stacked bar using a low-intensity color, as shown in Figs 2-4. For Fig 5, we have noted the totals with and without dietary emissions. Additionally, we have added the statement, "Average dietary emissions can be reduced through dietary change," to each figure caption. The updated figures and captions are shown below.

The issue of dietary emissions is addressed in the text with the following sentences:

Text

"Notably, the high average dietary emissions can be reduced by approximately 80% through dietary changes[31]."

"Similarly, sustainable diets have the potential to both lower dietary GHG emissions and provide health benefits[31]. Emissions from dietary choices are highly variable, influenced by individual diets and geographical factors[16,22,27,31.] The compensatory dietary intake associated with active modes of transportation remains uncertain and varies widely[5], with one study suggesting a range between 19% and 96%[16]. However, as an attributional life cycle assessment, this study fully considers the GHG intensity of the additional energy required for human effort for each transportation mode."

Results

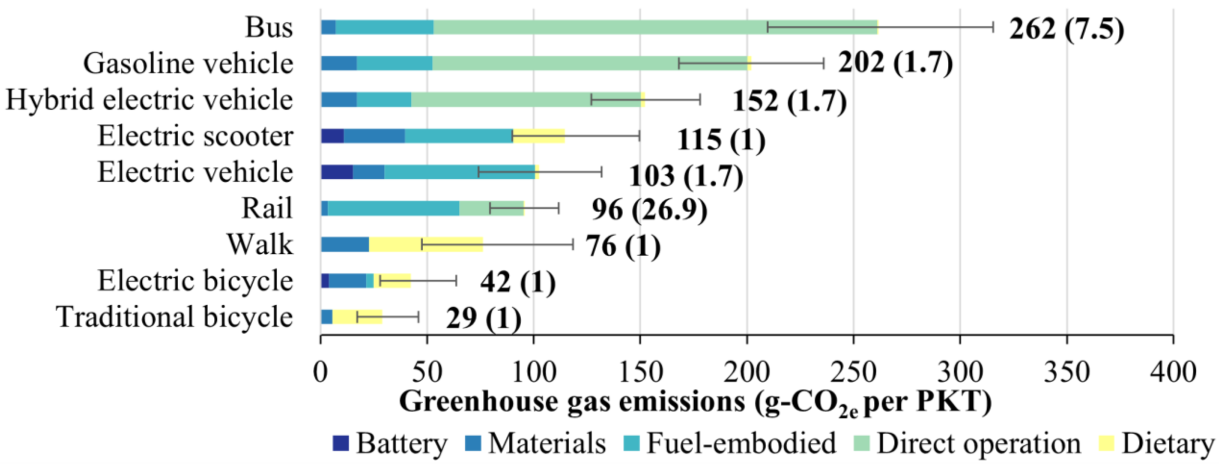

Fig. 2. Average greenhouse gas emissions of transportation mode compositions in 2023. The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The average ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); passenger kilometer traveled (PKT).

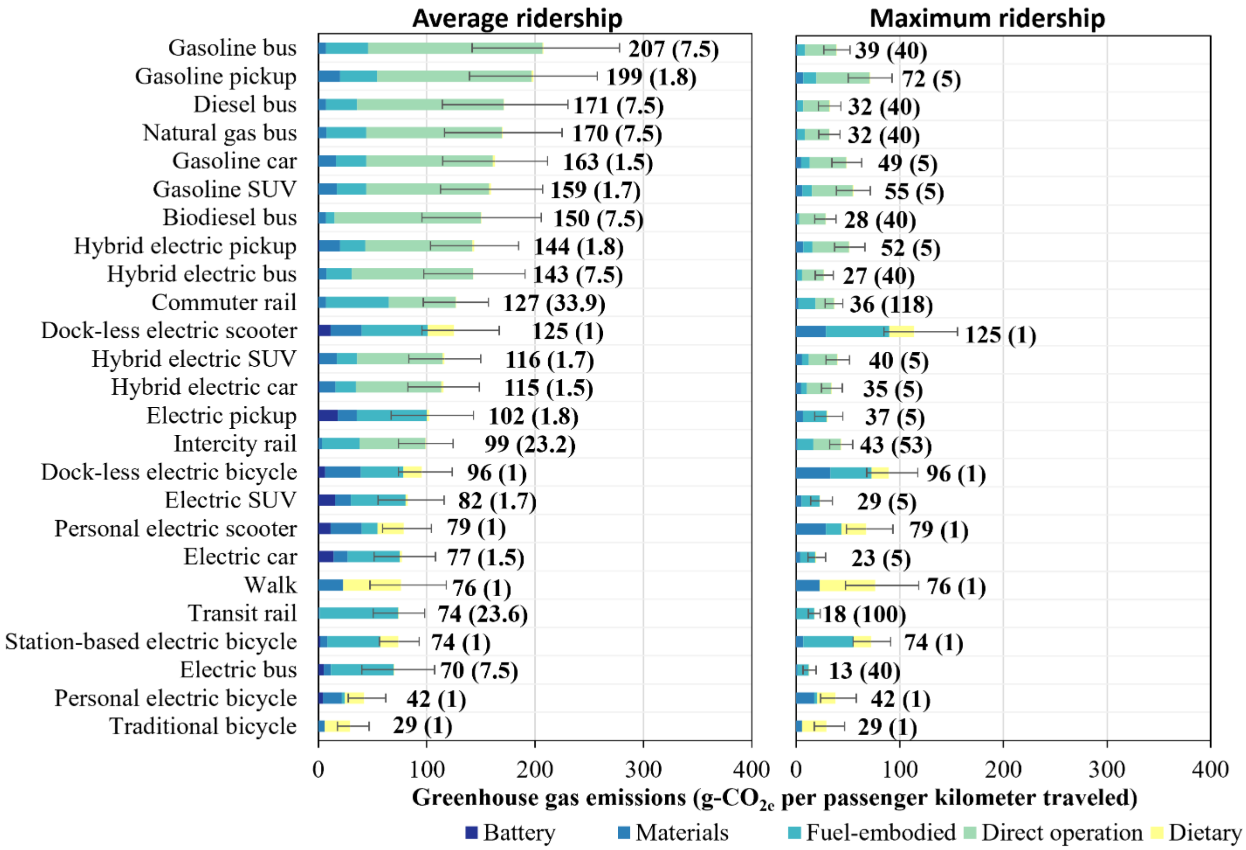

Fig. 3. Greenhouse gas emissions of 2023 transportation technology models. Results are presented for average ridership (left) and maximum ridership (right). The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); sport utility vehicle (SUV).

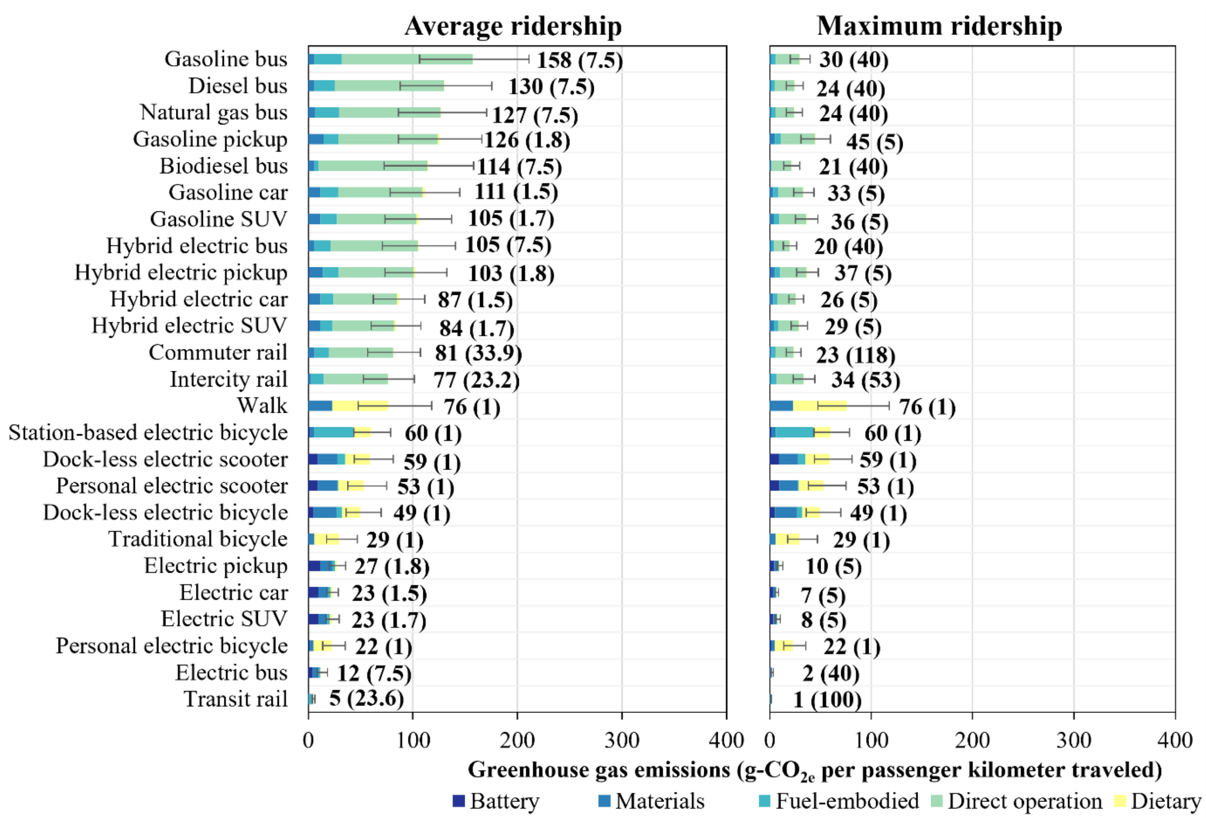

Fig. 4. Greenhouse gas emissions of 2050 transportation technology models with a decarbonized electricity grid. Results are presented for average ridership (left) and maximum ridership (right). The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); sport utility vehicle (SUV).

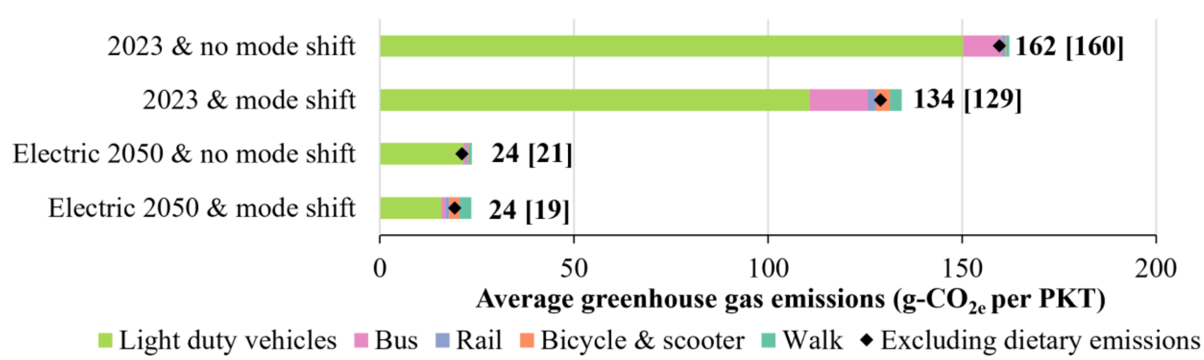

Fig. 5. Average urban greenhouse gas emissions from various transportation scenarios, including 2023 technology without mode shift, 2023 technology with mode shift, 2050 electric technology without mode shift, and 2050 electric technology with mode shift. The emissions are expressed as grams of Carbon Dioxide equivalent per passenger-kilometer traveled (g-CO_{2e} per PKT). Values within brackets exclude dietary emissions.

Comment 2.10

Discuss the results in the context of similar studies, e.g., this one: https://il.boell.org/sites/default/files/2021-03/Felix%20Creutzig%20-%20Making%20Smart%20Mobility%20Sustainable.pdf

Results are similar but not identical (based on ITF numbers in the case above) and it would be helpful to clarify differences and similarities.
Thank you for noting the usefulness of comparing our results to similar studies. We have included such a comparison in the following paragraph:

"The estimated GHG emissions for these transportation technologies can be compared to findings from other attributional life cycle assessments. Creutzig (2021) similarly found that personal electric scooters have much lower emissions (45 g-CO_{2e} per PKT) compared to shared electric scooters (120 g-CO_{2e} per PKT)[6]. Blonde et al. (2011) and Noussan et al. (2022) identified traditional bicycles (21 g-CO_{2e} per PKT) as having the lowest GHG intensity among travel modes when dietary emissions are included, though they did not consider walking and electric scooters[5,25]. Noussan et al. (2022) also reported substantially lower emissions for buses (48 g-CO_{2e} per PKT) and rail (33 g-CO_{2e} per PKT) than those shown in Fig. 3, likely due to different location-specific ridership and emissions factors[5]. Additionally, Noussan et al. (2022) reviewed light-duty vehicle GHG emissions, finding the mean higher than in Fig. 3, with 138 g-CO_{2e} per PKT for electric cars and 235 g-CO_{2e} per PKT for gasoline cars[5], which can be attributed to advancements in vehicle energy efficiencies over time."

Comment 2.11

Last but not least, consider picking up Ch10 of the IPCC 2022 report on climate solutions, where I believe micromobility does play a less pronounced role compared to fuel shift. That could serve as a motivation for your manuscript. Other publications also provide context (e.g., https://www.tandfonline.com/doi/pdf/10.1080/01441647.2015.1079277?casa_token=B2OgPGasjb4AAAAA:OXloCISbGwMFifFkYeowW0VHAWivcbT7if240cWkH_r-JrDIdedVo5kGy6aTi-myzcEB10xLJ84UQaM, and https://d1wqtxts1xzle7.cloudfront.net/100047018/annurev-environ-031913-100450-libre.pdf?1679245617=&response-content-disposition=inline;+filename=Energy_for_Transport.pdf&Expires=1712413658&Signature=WTWQw~vTY0Xs~LHQevkBZs~yQlMOuBWx95QcNJervWDsM7gzdkABNxNb~OqB9Mmm2iko1AlZlrCzft2-g5oxMw2NOgMFDpjtEsV0eB1PAoSLcPlHW~--vIdKM2kcX8PztMaSRRuUGEdUPvD0M49XOk7RK-bVDuu46OnSJyxeHUYTmyHGYJpna-DurWfh-lwdm8w8riRbcXOFs9-nJwmgmXuIMhIyzLtncAbd1EXiAFiqI-5SfQruu1qUuvrpG8xhhHyiW-yaZpU-oZ05A8ldY0Ea1fnIt~srlRM2vIdeXlDj4rGBuh62DUO1Q5XQE-p1Nv-6WxQLJMuTsB2b~BZhkg__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA).
Thank you for pointing out that the introduction could be enhanced by improving the motivation of the manuscript and for sharing resources to provide context. Please find the updated introduction section below, which highlights the motivations and contributions of the study:

Introduction

"The urgent need for the decarbonization of the transportation sector has become a paramount concern for the United States in recent years[1]. In 2021, the United States transportation emissions accounted for 29% of the nation's total greenhouse gas (GHG) emissions[2]. To achieve ambitious climate goals[1], it has become imperative to address the emissions associated with the transportation sector comprehensively.

National efforts to mitigate GHG emissions from transportation in the United States have centered on three key objectives: increasing convenience, improving efficiency, and transitioning to cleaner options[1]. These endeavors are aimed at reducing the total vehicle kilometers traveled (VKT), increasing ridership, enhancing fuel economy, and adopting technologies that offer low emissions both presently and in the future[1]. However, this transformation has several challenges.

The United States currently has the highest passenger kilometers traveled (PKT) per capita globally, which is accompanied by low ridership of public transportation[3]. Additionally, the country maintains a substantial fleet of aging and inefficient vehicles, and a heavy reliance on petroleum-based fuels[4]. As such, addressing the transportation sector's emissions necessitates a comprehensive understanding of the emissions profiles of average, current, and future vehicle models, as well as the identification of societal and technological solutions.

Several studies have assessed the GHG emissions associated with various modes of inland transportation. Noussan et al. (2022) reviewed and compared the GHG emissions factors of passenger transportation modes, finding that bicycles and rail had the lowest GHG emissions, while cars had the highest[5]. This study surveyed available literature from specific locales, capturing the mean rather than the United States average[5]. Creutzig (2021) compared the GHG emissions of active transportation modes to buses, rail, and cars in Germany and Israel, discovering that shared electric scooters had higher emissions than buses and rail but lower emissions than cars with one occupant[6]. Moreover, Creutzig (2021) found private bicycles and electric scooters to have the lowest emissions among the modes considered, though these results do not use United States parameters[6]. For instance, Figueroa et al. (2014) noted that the energy intensity of buses per PKT in the United States is much higher than the rest of the world due to low ridership, highlighting the importance of evaluating GHG emissions specific to United States parameters[7]. These studies have been limited in scale and have not deliberately calculated the United States average, which is needed to compare and contextualize GHG emissions reductions possible through mode shifts and technology advancements on an impactful nationwide scale to inform transportation and energy sector policy.

This study aims to address these critical issues by leveraging data on the United States average passenger load factors, fuel economies across vehicle ages, and the technological composition of various inland transportation modes. It employs a robust methodology, including consistent assumptions for mode comparisons, Monte Carlo simulations to capture uncertainty, and the inclusion of dietary emissions associated with each mode. By comprehensively assessing the attributional life cycle emissions associated with each mode, this research provides valuable insights into GHG emissions in the United States transportation sector, providing a transparent breakdown of emissions for each mode, including both current conditions and potential future advancements. The assessment involves the determination of total PKT and GHG emissions for each transportation mode based on their current technological profiles. Moreover, the study explores current technology models and high ridership scenarios to identify technologies capable of reducing emissions. It also projects GHG emissions for 2050, assuming a decarbonized electricity grid, and highlights each technology's potential for emissions reduction. Finally, the research contextualizes the results in terms of emissions reductions achievable through urban mode shifts and a transition to technologies using decarbonized electricity. The study finds that while shifting to public transportation and active modes can reduce GHG emissions, advancements in technology and electrification have a greater potential for reducing emissions by up to 85% by 2050. The results indicate that the majority of GHG emissions reductions can be achieved through fuel shifts alone, with mode shifts providing modest reductions in the near-term and minimal reductions in the long-term."

Reviewer #3 (Remarks to the Author):

We thank the reviewer for the careful review and suggestions. Accordingly, we have made major changes to the manuscript.

Comment 3.1

Currently, the study lacks the types of checks one would expect from a high-quality work relying on life cycle assessment, namely sensitivity and uncertainty analyses, complemented by validation against literature. Any error or approximation in a critical input parameter can change the study's conclusion. Hence, special attention needs to be paid to ensure critical input values are robust and correct, and, very importantly, the reader should be able to judge this by presenting such inputs in a clear and transparent manner.

Thank you for the suggestion. We have performed a sensitivity analysis for each result and a Monte Carlo uncertainty analysis for the 5 most sensitive inputs for each result. Due to the inclusion of 71 results in the study and 317 inputs, the sensitivity analysis results are shown in the published Excel workbook. The results of the Monte Carlo analysis are illustrated in each of the figures through the inclusion of the mean value and error bars representing the 95% confidence interval (see Comment 3.9). We have also added a paragraph to the results section highlighting the impact of uncertainty, which is provided below.

Additionally, we have carefully checked the selection of each input parameter from reliable and robust sources. The input values have been listed and cited in Tables 1 through Table 6 of the manuscript, which are provided below.

<u>Text:</u>

"The impact of uncertainty meaningfully affects the ranking of the cleanest transportation modes. Variability in input data, such as vehicle efficiency and operational characteristics, introduces a range of possible emission outcomes. Monte Carlo simulations help quantify this uncertainty by generating a distribution of potential average emissions for each mode. Consequently, while some modes may appear cleaner on average, the overlapping confidence intervals indicate that these rankings are not absolute. For instance, slight variations in dietary emissions or vehicle usage patterns can shift the relative positions of buses, light duty vehicles, and active transportation modes. This highlights the importance of considering uncertainty in environmental assessments to ensure that strategies remain effective under various real-world conditions."

Tables

Table 1. Occupancy by vehicle type.

Parameter	Value	Units
Car occupancy	1.5 [4]	Passengers
SUV occupancy	1.73 [4]	Passengers
Pickup truck occupancy	1.8 [4]	Passengers
Bus occupancy	7.5 [4]	Passengers
Intercity rail occupancy	23.2 [4]	Passengers
Transit rail occupancy	23.6 [4]	Passengers
Commuter rail occupancy	33.9 [4]	Passengers
Electric bicycle	1	Passenger
Traditional bicycle	1	Passenger
Walking	1	Passenger
Electric scooter	1	Passenger

Table 2. Parameters to calculate dietary energy intake per kilometer traveled.

Parameter	Value	Units
Walking metabolic equivalent of task	3.5 [28]	Kilocalorie per kilogram per hour
Traditional bicycle metabolic equivalent of task	6.8 [24]	Kilocalorie per kilogram per hour
Electric bicycle metabolic equivalent of task	5.9 [24]	Kilocalorie per kilogram per hour
Electric scooter metabolic equivalent of task	2.8 [28]	Kilocalorie per kilogram per hour
Light-duty vehicle operator metabolic equivalent of task	2.0 [28]	Kilocalorie per kilogram per hour
Bus operator metabolic equivalent of task	2.5 [28]	Kilocalorie per kilogram per hour
Train operator metabolic equivalent of task	2.5 [28]	Kilocalorie per kilogram per hour
Walking speed	4.8 [28]	Kilometers per hour
Bicycle speed	21.1 [24]	Kilometers per hour
Electric bicycle speed	24.6 [24]	Kilometers per hour
Electric scooter speed	8.4 [29]	Kilometers per hour
Light-duty vehicle speed	45 [4,41]	Kilometers per hour
Bus speed	44 [4,41]	Kilometers per hour
Intercity rail speed	20 [4]	Kilometers per hour
Transit rail speed	11 [4]	Kilometers per hour
Commuter rail speed	20 [4]	Kilometers per hour

Table 3. Energy efficiencies for each vehicle type.

Parameter	Value	Units
Electric car energy efficiency 2023	0.23 [21]	kWh/VKT
Electric car energy efficiency 2050	0.20 [21]	kWh/VKT
Electric sport utility vehicle energy efficiency 2023	0.29 [21]	kWh/VKT
Electric sport utility vehicle energy efficiency 2050	0.24 [21]	kWh/VKT

Electric pickup truck energy efficiency 2023	0.38 [21]	kWh/VKT
Electric pickup truck energy efficiency 2050	0.31 [21]	kWh/VKT
Electric scooter energy efficiency	0.029 [42]	kWh/VKT
Electric bicycle energy efficiency	0.0061 [24]	kWh/VKT
Electric bicycle electricity output	150 [24]	Watts
Gasoline car fuel economy 2050	31 [21]	MPGGE
Gasoline car fuel economy 2050	44 [21]	MPGGE
Gasoline sport utility vehicle fuel economy 2023	27 [21]	MPGGE
Gasoline sport utility vehicle fuel economy 2050	41 [21]	MPGGE
Gasoline pickup truck fuel economy 2023	21 [21]	MPGGE
Gasoline pickup truck fuel economy 2050	32 [21]	MPGGE
Hybrid car fuel economy 2023	46 [21]	MPGGE
Hybrid car fuel economy 2050	59 [21]	MPGGE
Hybrid sport utility vehicle fuel economy 2023	40 [21]	MPGGE
Hybrid sport utility vehicle fuel economy 2050	53 [21]	MPGGE
Hybrid pickup truck fuel economy 2023	30 [21]	MPGGE
Hybrid pickup truck fuel economy 2050	42 [21]	MPGGE
Diesel bus 2023	6.3 [21]	MPGDE
Diesel bus 2050	8.2 [21]	MPGDE
Biodiesel bus 2023	6.3 [21]	MPGDE
Biodiesel bus 2050	8.2 [21]	MPGDE
Gasoline bus 2023	5.0 [21,43]	MPGDE
Gasoline bus 2050	6.4 [21,43]	MPGDE
Hybrid bus 2023	7.7 [21]	MPGDE
Hybrid bus 2050	10.3 [21]	MPGDE
Electric bus 2023	18.9 [21]	MPGDE
Electric bus 2050	28.2 [21]	MPGDE
Natural gas bus 2023	5.4 [21]	MPGDE
Natural gas bus 2050	6.9 [21]	MPGDE

Abbreviations: miles per gallon of gasoline equivalent (MPGGE); miles per gallon of diesel equivalent (MPGGE); kilowatt-hour (kWh); vehicle kilometer traveled (VKT).

Table 4. Lifetime of vehicles.

Parameter	Value	Units
Traditional bicycle lifetime	19,200 [25]	Vehicle kilometers traveled
Electric bicycle lifetime	19,200 [25]	Vehicle kilometers traveled
Electric scooter frame lifetime	6,529 [40]	Vehicle kilometers traveled
Electric scooter battery lifetime	3,509 [40]	Vehicle kilometers traveled
Shoe lifetime	644	Vehicle kilometers traveled
Bus lifetime	881,000 [18]	Vehicle kilometers traveled
Car lifetime	278,600 [21]	Vehicle kilometers traveled
Sport utility vehicle lifetime	295,031 [21]	Vehicle kilometers traveled
Pickup truck lifetime	295,031 [21]	Vehicle kilometers traveled

Table 5. Greenhouse gas intensities of diets, electricity, and batteries.

Parameter	Value	Units
United States average dietary intensity	2.54 [22]	kg-CO_{2e} per capita per day
2023 electricity intensity	494 [21]	g-CO_{2e} per kWh
2050 electricity intensity	29 [21]	g-CO_{2e} per kWh
LFP 2023 battery intensity	79 [21]	kg-CO_{2e} per kWh of battery capacity
LFP 2050 battery intensity	64 [21]	kg-CO_{2e} per kWh of battery capacity
NMC622 2023 battery intensity	80 [21]	kg-CO_{2e} per kWh of battery capacity
NMC622 2050 battery intensity	61 [21]	kg-CO_{2e} per kWh of battery capacity

Abbreviations: lithium iron phosphate (LFP); nickel manganese cobalt (NMC); kilogram (kg); gram (g); kilowatt-hour (kWh); carbon dioxide equivalent (CO_{2e}).

Table 6. Battery size for each electric vehicle.

Parameter	Value	Units
Electric car battery size 2023	74 [21]	Kilowatt-hour
Electric car battery size 2050	61 [21]	Kilowatt-hour
Electric sport utility vehicle battery size 2023	99 [21]	Kilowatt-hour
Electric sport utility vehicle battery size 2050	77 [21]	Kilowatt-hour
Electric pickup truck battery size 2023	120 [21]	Kilowatt-hour
Electric pickup truck battery size 2050	93 [21]	Kilowatt-hour
Electric scooter battery size	0.48 [44]	Kilowatt-hour
Electric bicycle battery size	0.96 [45]	Kilowatt-hour
Electric bus battery size	200 [46]	Kilowatt-hour

Comment 3.2

Additionally, this study feels incomplete. It informs on the potential GHG emission reductions by shifting towards collective means of transport and increasing their occupancy rate, but the reader never really gets to see the “big picture”, i.e., the fleet-level GHG emissions reduction potential.

In my opinion, the study stops a step too early, i.e., the comparison of GHG emissions per passenger-kilometer. I believe this substantially reduces the added value of the work because while the study tells us that some modes of transportation are much more efficient than others, this is not new. Studies (e.g., https://doi.org/10.1016/j.jclepro.2020.122898, https://doi.org/10.1007/978-3-319-58538-3_192-1, https://www.mdpi.com/2071-1050/12/18/7548, are a few ones I could find in a few minutes), databases (e.g., ecoinvent) and tools (e.g., mobitool, GREET) already give us the lifecycle-based GHG emission factors across transportation, even though they may not have a strictly similar technological, temporal or geographical scope. Existing studies have not told us yet whether, at scale, those lifecycle-based emission reductions are important or not (or even feasible), which is something your study currently falls short of.

Hence, I regret to say that, while quite informative, the scope needs to be widened to the fleet level (not simply multiplying the GHG emission factors by the demand, but also accounting for realistic modal shifts given trip distances, infrastructure capacity, etc.). Without this, I do not see the novelty of this work (at least, not the standards of a Nature Portfolio journal).

Thank you for the suggestion, we have added a fleet-level GHG emissions reduction section to the study. The section is shown below:

Urban fleet transition

"The impact of transitions and advancements is demonstrated through an urban fleet transition in Fig. 5, which features different combinations of mode shifts and electrification. The urban mode shift scenarios are derived from Fulton et al. (2024)[32]. Scenarios without a mode shift comprise 91% light-duty vehicles, 6% bus, 1% rail, 1% bicycle and scooter, and 1% walking. The mode shift scenarios encompass a transition away from light-duty vehicles (67%) and towards increased use of buses (17%), rail (3%), bicycles and scooters (10%), and walking (4%). Based on the ratio of new vehicles required according to Fulton et al. (2024) and the increase in bus and rail from the mode shifts, the load factors for bus and rail increase by a factor of 1.5 and 2.2, respectively[32]. Additionally, the current make-up of 2023 technologies from Fig. 3 is modeled and compared to 2050 technologies (Fig. 4), with buses and light-duty vehicles being fully electric in 2050. Notably, a limitation of the study is that the GHG emission factors represent national averages and are not specifically tailored to urban contexts. The results show that transitions to electrified powertrains and advancements in technologies by 2050 have a greater impact on average GHG emissions than urban mode shifts. The results are presented with and without dietary emissions.

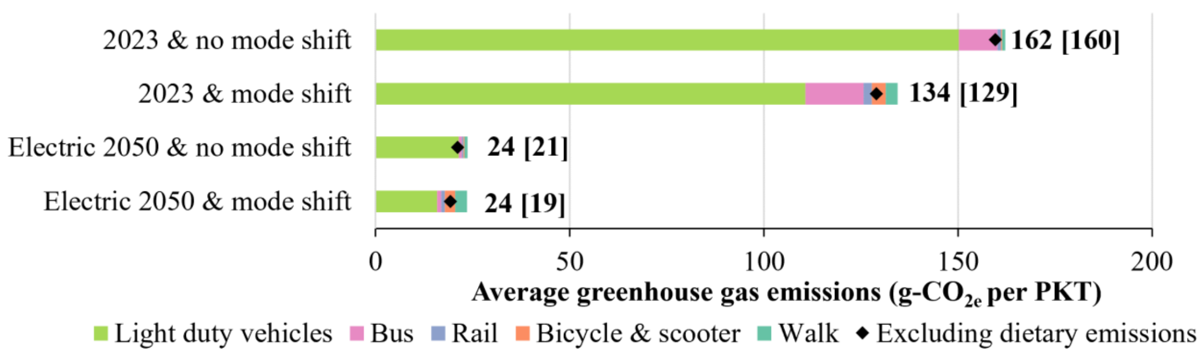

Fig. 5. Average urban greenhouse gas emissions from various transportation scenarios, including 2023 technology without mode shift, 2023 technology with mode shift, 2050 electric technology without mode shift, and 2050 electric technology with mode shift. The emissions are expressed as grams of Carbon Dioxide equivalent per passenger-kilometer traveled (g-CO_{2e} per PKT). Values within brackets exclude dietary emissions.

As shown in Fig. 5, the transition to electrified transportation technologies in 2050 dramatically reduces GHG emissions per PKT compared to 2023 technology, both with and without mode shift. Incorporating mode shifts in 2023 reduces GHG emissions, highlighting the benefits of reducing light-duty vehicle travel in the near-term. In 2050, including mode shifts does not alter GHG emissions when dietary emissions are taken into account, as electric vehicles exhibit lower total GHG emissions than walking and electric scooters and similar emissions to electric and traditional bicycles (Fig. 4)."

Comment 3.3

I have some additional and more detailed remarks below.

Title: the study has a USA scope of analysis. This should be reflected in the title.
Thank you for identifying that the locational scope needs to be reflected in the title. Please find the updated title below:
"Evaluating present and future climate impacts of transportation modes in the United States"

Comment 3.4

Abstract: "This study suggests that the greatest emissions reductions can be achieved through adopting technologies energized by decarbonized electricity and changing travel behavior." This seems to be presented as the study's main "take-away" message. But this is not really teaching us anything new about the challenge of decarbonizing the transport sector. Electrifying transport, coupled with low-carbon electricity and an increased occupancy rate, have been known levers to reduce GHG emissions from the past decade or so.
Thank you for pointing out that the takeaways of the study needed improvement in the abstract. Please find the updated abstract below with the takeaways highlighted:

"Decarbonizing the United States transportation sector has emerged as a critical objective to combat climate change due to its high greenhouse gas (GHG) emissions, largely from light-duty vehicles. This study assesses the breakdown of life cycle emissions of various transportation options under average and maximum ridership scenarios and quantifies emissions reductions through mode shifts and technology advancements. Electrified transportation achieves half the GHG emissions of petroleum-fueled options as of 2023, with projections indicating a reduction to one-fifth by 2050. Battery systems contribute up to one-fifth of lifetime emissions of electric vehicles and buses as of 2023, and this share is estimated to increase to half by 2050 as electric fuel emissions are greatly reduced with decarbonized electricity. The study concludes that shifting away from light-duty vehicles can achieve near-term GHG reductions, but these reductions are minimal in the long term when combined with transportation electrification powered by decarbonized electricity."

Comment 3.5

Main

p.1 l.26: I am not convinced the goal is to reduce the total passenger-kilometers. Instead, the goal is probably to reduce the number of vehicle-kilometers (and favor the most efficient vehicles) while keeping the same level of service (i.e., passenger kilometers).
Thank you for identifying that this sentence needed to be rewritten. Please find the updated sentence below:
"These endeavors are aimed at reducing the total vehicle kilometers traveled (VKT), increasing ridership, enhancing fuel economy, and adopting technologies that offer low emissions both presently and in the future[1]."

Comment 3.6

Ref. 15 is not a peer-reviewed academic work, but a white report from the ICCT, subjected to an internal and partly external (but non-anonymous) review. I strongly suggest favouring single-blind peer-reviewed academic sources. Additionally, the buses and other heavy-duty vehicles modelled in this ICCT report are specific in mass and fuel consumption to the EU market, which

differs from your geographical scope. At the same time, you indicate the use of the GREET model for buses, so please be more specific on the role of Ref. 15.
Thank you for your valuable feedback regarding Ref. 15 (now Ref 18) by O'Connell et al. (2023). We have clarified in the Methods section where the values from O'Connell et al. (2023) are used in the study, as detailed below.

Methods

"In the case of compressed natural gas buses, material emissions were assumed to be 6% higher compared to diesel bus emissions based on O'Connell et al. (2023)[18]."

"Based on O'Connell et al. (2023), these buses were modeled to have an operational lifespan of 881 thousand VKT[18], which is consistent with Federal Transit Administration guidelines found in Laver et al. (2007)[51]."

While we acknowledge that Ref. 15 is a white paper from the ICCT and not a single-blind peer-reviewed academic work, we included it in our study for several reasons:

- The ICCT is a well-regarded organization with extensive expertise in transportation emissions. Their reports, while not peer-reviewed in the traditional academic sense, undergo rigorous internal and external review processes. This particular report provides comprehensive data and insights on heavy-duty vehicle emissions, which are highly relevant to our study.
- The ICCT report serves as a complementary data source to enhance our modeling assumptions. For instance, the material emissions for CNG buses being 6% higher than diesel buses is a detail that is critical for our analysis and not readily available from other sources.
- We recognize that the ICCT report focuses on the EU market, which differs from our geographical scope. However, the lifetime of EU bus technology in this study aligns with the Federal Transit Administration's guidelines for a minimum bus life of 500,000 miles (Laver et al. (2007)).

Laver, Richard et al. Useful Life of Transit Buses and Vans Final Report. https://www.transitwiki.org/TransitWiki/images/6/64/Useful_Life_of_Buses.pdf (2007).

Comment 3.7

p.3 l.3: you cannot draw conclusions on the environmental impacts of a system solely based on its GHG emissions. Please reformulate.
Thank you for recognizing the need for this distinction. We have replaced "environmental impact" with "GHG emissions" in the sentence below:

"Finally, active forms of transport, such as walking, traditional bicycles, electric bicycles, and electric scooters, collectively represent less than 1% of PKT and GHG emissions in the United States, emphasizing their minimal GHG emissions compared to traditional transport modes."

Comment 3.8

Furthermore, as you rightly point out in the Methods section, emissions related to active modes of transport are sensitive to the diet. You should at least mention the type of diet considered to provide the additional effort needed to move the vehicle (e.g., US-average, protein-rich, meat-based, etc.)

Thank you for identifying that the diet was not described. We have added the following sentences to the manuscript:

"…; dietary emissions, which represent the United States average emissions from the caloric intake needed to fuel human effort for each form of travel"

"Notably, the high average dietary emissions can be reduced by approximately 80% through dietary changes[31]."

"Similarly, sustainable diets have the potential to both lower dietary GHG emissions and provide health benefits[31]. Emissions from dietary choices are highly variable, influenced by individual diets and geographical factors[16,22,27,31]."

"Emissions resulting from human effort were calculated using dietary GHG emissions from Bassi et al. (2022) of 2.54 kg-CO_{2e} per capita per day ($Fuel_{normal}$), which captures the decline of dietary GHG emissions in the United States[22]."

Comment 3.9

Figure 2 gives the impression of robust and certain numbers. GHG emissions from collective means of transport are very sensitive to use-related parameters, such as lifetime and occupancy rate. Active means of transport are sensitive to the food diet. Electrified means of transport are sensitive to battery chemistry, capacity and carbon intensity of the electricity. The reader would expect a more sophisticated figure, showing all these nuances, uncertainty and effects of modelling choices. This is especially the case when it currently shows that collective and active means of transport (i.e., bus and walking) emit more GHG than passenger cars.

Thank you for the suggestion. Please find the updated Figs 1-4 below, along with details of the analysis under Comment 3.1.

Results

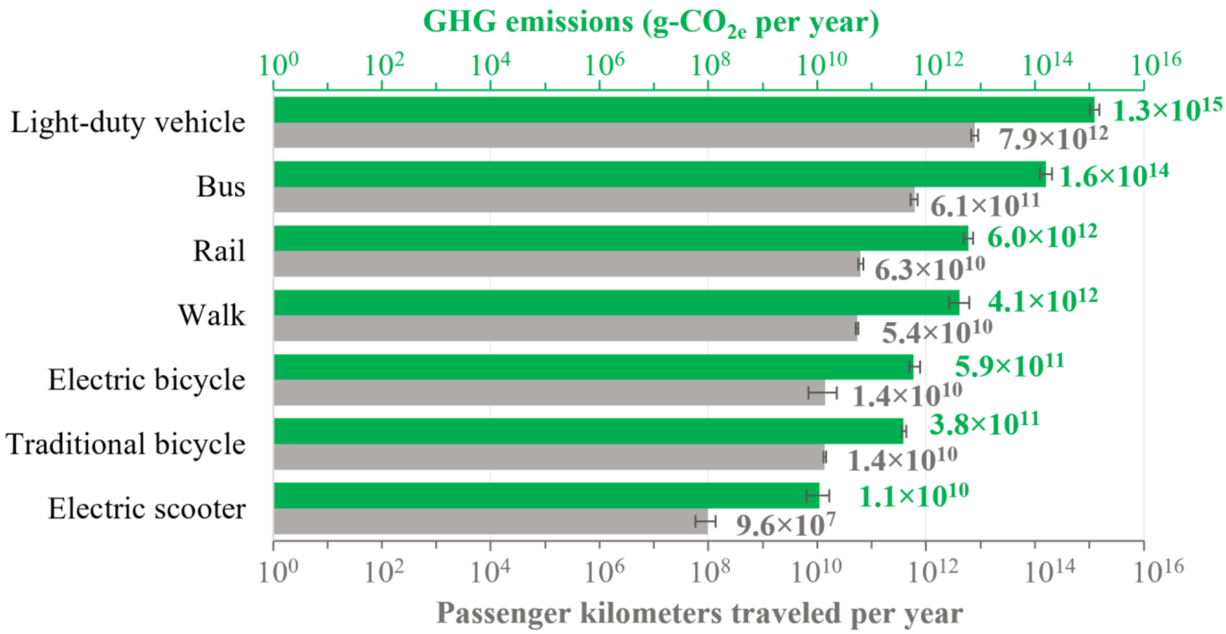

Fig. 1. Passenger kilometers traveled (PKT) and greenhouse gas (GHG) emissions of transportation modes in the United States. Greenhouse gas emissions include all stages over the life cycle of each transportation mode. The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}).

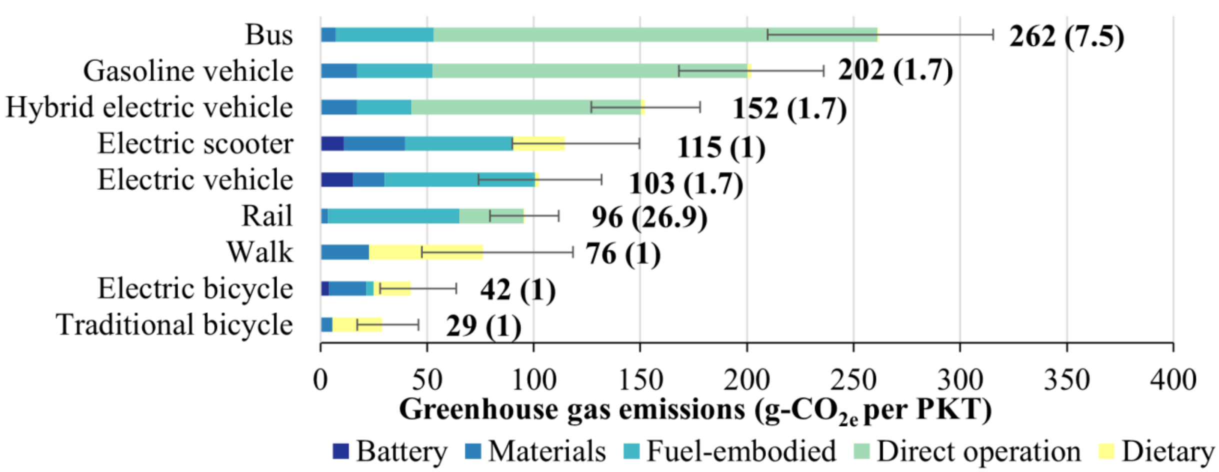

Fig. 2. Average greenhouse gas emissions of transportation mode compositions in 2023. The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The average ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); passenger kilometer traveled (PKT).

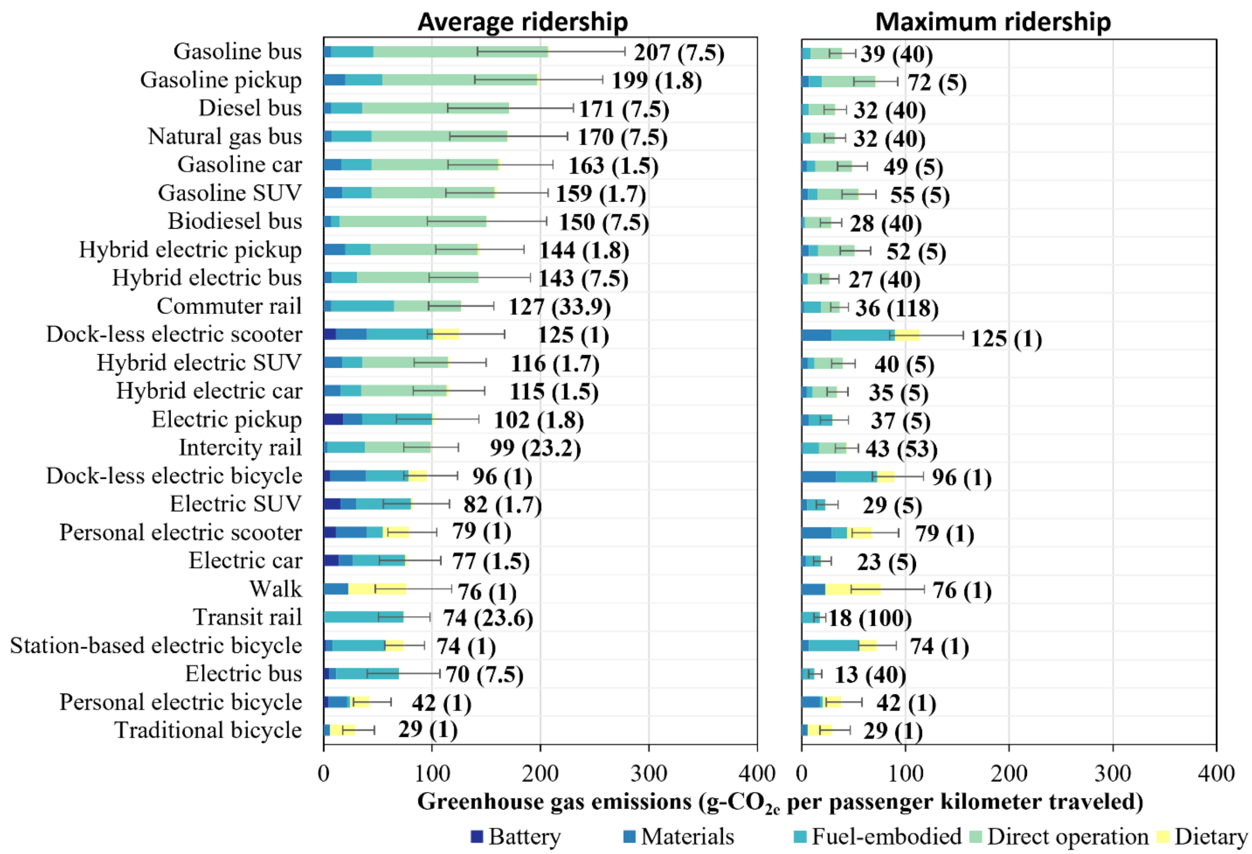

Fig. 3. Greenhouse gas emissions of 2023 transportation technology models. Results are presented for average ridership (left) and maximum ridership (right). The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); sport utility vehicle (SUV).

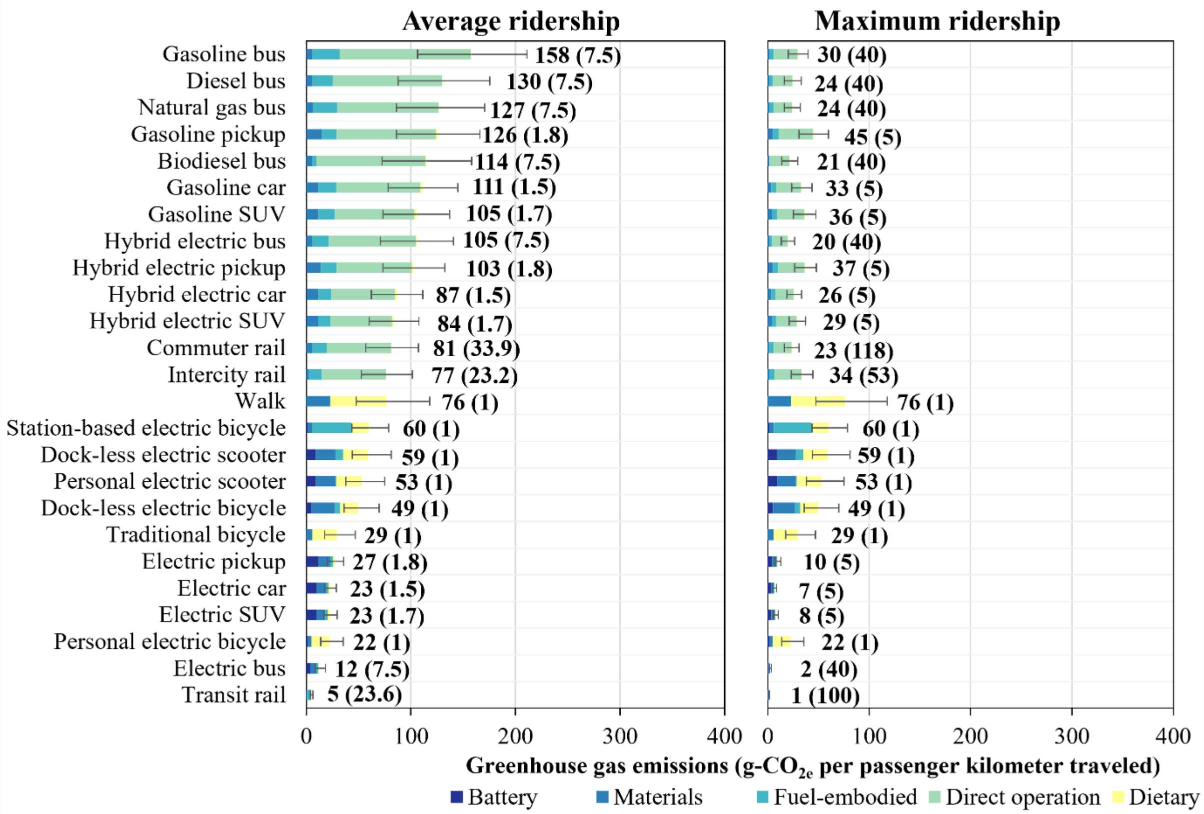

Fig. 4. Greenhouse gas emissions of 2050 transportation technology models with a decarbonized electricity grid. Results are presented for average ridership (left) and maximum ridership (right). The values represent the mean of the Monte Carlo simulation, with error bars indicating the 2.5th and 97.5th percentiles. The ridership for each mode is shown in parentheses next to the mean value. Average dietary emissions can be reduced through dietary change. Abbreviations: grams (g); Carbon Dioxide equivalent (CO_{2e}); sport utility vehicle (SUV).

Comment 3.10

Also, I struggle with the fact of comparing walking and driving without nuances. While one may substitute the other, this is only really the case in urban contexts, for very short distances. Yet, you model your vehicles using national statistics and average traffic situations (including fuel consumption). This is incorrect in my opinion. The transportation modes you present only compete on certain market segments, such as urban mobility. Hence, to keep this comparison valid, I suggest redefining the scope of the analysis of urban mobility options and modifying the vehicles' specifications accordingly (and the manuscript's title, too).

Thank you for your feedback. Here is our response to your concerns:

- Using national statistics and average traffic situations ensures broad applicability and reflects typical conditions. This allows us to capture the overall impact of different transportation modes, both urban and non-urban. We believe this is major contribution of our study.
- We acknowledge the nuanced differences between walking and driving, particularly their substitution limitations. Our intent was to provide a broad perspective on potential

greenhouse gas emissions across various transportation options. We have added the following sentences to the discussion to mention this limitation:
  - "Shifts in transportation modes away from light-duty vehicles are largely constrained by locational factors, with the adoption of public transportation and active modes primarily limited to urban areas[25,34]."
  - "Active transportation also requires safe infrastructure, which may need to be expanded, and is best suited for short trip distances, limiting its usage[34]."
- We have tailored a portion of our study to urban mobility by including a fleet level transition for urban areas. We have also clearly noted in the results that a limitation of our study is GHG emissions of vehicles are based on averages rather than exclusively urban contexts:
  - "Notably, a limitation of the study is that the GHG emission factors represent national averages and are not specifically tailored to urban contexts."

Comment 3.11

Additionally, electric scooters are known to have a relatively short lifetime. It is surprising to see them having lower GHG emissions than bicycles. One would expect higher GHG emissions from the scooter itself (because it is normalized by a lower lifetime), while lower emissions from electricity use. You refer to Ref.16 for a lifetime of 10,000 km, but Ref. 16 uses a lifetime of 2,117 km for electric scooters. Why such a difference?
Thank you for recognizing that this input requires an explanation. The initial short lifetimes of electric scooters, as referenced in literature from around 2018, have been continually cited without accounting for market evolution. Over the past six years, manufacturers have significantly extended the lifespan of electric scooters. Leading models now have expected lifespans of almost 5 years. This improvement in durability is why our analysis assumes a longer lifespan for electric scooters, resulting in lower normalized GHG emissions. We have updated the lifespan of the electric scooter frame (6,529 km) and battery (3,509 km) to values reported in a recent industry study by Hanson et al. (2022). We have clarified this in the text with the following sentence:

"The lifespan of the electric scooters is modeled to be longer than in existing literature to account for the manufacturing improvements in the industry, as detailed in Hanson et al. (2022)[40]."

Hanson, M., Chester, M., Gowland, K., Cherry, C. & Cazzola, P. How Long Do E-Scooters Last?
https://static1.squarespace.com/static/6345fbec294601073a26d0c6/t/637b90e7b9d9515367f7c810/1669042872669/How+Long+do+E-scooters+Last%3F+Nov+%2722.pdf (2022).

Comment 3.12

The lifetime value of bicycles is from Ref. 35. In this document, they calculate the lifecycle-based GHG emission per PKT and find a total of 21 gCO2e. This contrasts quite a bit with your number (107 gCO2e). Can this really be explained by a difference in diet? It is necessary that you validate your per PKT numbers against the literature to assert the robustness of your results.
Thank you for bringing this to our attention. We have chosen a different source (Bassi et al. (2022)) for our dietary GHG emissions which is specific to the United States and accounts for recent reductions in dietary GHG emissions. We have validated this value with other studies in

literature such as Heller and Keoleian (2014). The updated GHG emissions intensity of traditional bicycles is 29 g-CO_{2e} per PKT.

We have also compared our results to literature in response to Comment 3.15 below.

Comment 3.13

I believe that if I continued searching for other vehicles, I'd keep finding such differences between assumptions and input values used in the literature and those you used. Hence, it is important you do this work yourself and justify your choices and their effects in a transparent manner.

Thank you for recognizing the diversity of input values from the literature and suggesting that we explain our chosen inputs. We are publishing our Excel workbook with this study to enable the scientific community to model results using their input values. We have diligently cited the sources from the literature that we modeled throughout our Excel workbook. This Excel workbook also includes results from our sensitivity analysis, demonstrating the effects of each input value. Additionally, we have provided justifications for specific inputs that require further explanation below. Other input values are clearly marked and cited from highly reputable sources.

"The dietary emissions for light-duty vehicles were based on the MET of driving and speed of the vehicle. The average speed of the vehicle (45 kph) was derived from a combination of national average highway (77 kph) and city (34 kph) speeds[4] and the amount of highway (25%) versus city (75%) VKT in 2022[40]. "

"Emissions resulting from human effort were calculated using dietary GHG emissions from Bassi et al. (2022) of 2.54 kg-CO_{2e} per capita per day ($Fuel_{normal}$), which captures the decline of dietary GHG emissions in the United States[22]."

"The standard MET value was modeled as 1.5 (MET_{normal}), which is consistent with other studies[16,25]."

"The dietary emissions for buses were based on the MET of the bus operator (2.5[28]) and speed of the bus. The average speed of a bus (44 kph) was derived from a combination of average highway (77 kph) and city (34 kph) speeds[4] and the amount of highway (23%) and city (77%) VKT in 2022[40]."

"The train operator was assumed to have the same 2.5 MET as a bus operator[28]."

"Notably, the MET values from Alessio et al. (2021) were selected for electric bicycles and traditional bicycles, as systematic reviews indicate that electric bicycles have an MET approximately 0.83 lower than traditional bicycles[52]. Alessio et al. (2021) also provided the necessary combination of MET, speed, and electrical output for electric bicycles, with an MET for traditional bicycles that is consistent with the literature[28]."

"The lifespan of the electric scooters is modeled to be longer than in existing literature to account for the manufacturing improvements in the industry, as detailed in Hanson et al. (2022)[43]."

Comment 3.14

In summary, and for the sake of clarity, I strongly suggest:
1. Adding a table in the Methods sections, showing all the important parameters for all vehicles (lifetime in kilometers and years, occupancy, fuel economy/food intake, mass, battery capacity, etc.), and the uncertainty range and source. Also, indicate clearly the GHG emission factor per unit of fuel/food/electricity (e.g., gCO2e/MJ) and those for battery manufacture (kg CO2e/kWh of battery capacity). While this information is mainly present already, it is scattered and hard to compare across vehicles. Your study will benefit a lot from such clarity and transparency.
Thank you for the suggestion to improve the transparency of the study. We have added the data tables under Comment 3.1 and are releasing our Excel workbook to enable reproducibility.

Comment 3.15

2. Adding some results validation, comparing your input values and emission factors and results with those of the literature. Hopefully, this will help you detect inconsistencies.
Thank you for recommending that we compare our results to existing literature. Please find the comparison below:

"The estimated GHG emissions for these transportation technologies can be compared to findings from other attributional life cycle assessments. Creutzig (2021) similarly found that personal electric scooters have much lower emissions (45 g-CO_{2e} per PKT) compared to shared electric scooters (120 g-CO_{2e} per PKT)[6]. Blonde et al. (2011) and Noussan et al. (2022) identified traditional bicycles (21 g-CO_{2e} per PKT) as having the lowest GHG intensity among travel modes when dietary emissions are included, though they did not consider walking and electric scooters[5,25]. Noussan et al. (2022) also reported substantially lower emissions for buses (48 g-CO_{2e} per PKT) and rail (33 g-CO_{2e} per PKT) than those shown in Fig. 3, likely due to different location-specific ridership and emissions factors[5]. Additionally, Noussan et al. (2022) reviewed light-duty vehicle GHG emissions, finding the mean higher than in Fig. 3, with 138 g-CO_{2e} per PKT for electric cars and 235 g-CO_{2e} per PKT for gasoline cars[5], which can be attributed to advancements in vehicle energy efficiencies over time."

Comment 3.16

3. The first two points should somehow be reflected in Figure 2 and, ultimately, Figures 3 and 4, showing the variability in results due to uncertainty and modelling choices.
Thank you for the suggestion. We have included uncertainty in our revised manuscript figures.

Comment 3.17

Figure 3: the current and maximum occupancy values should be included in this figure.
Thank you for the suggestion. We have added the occupancy values in parentheses in Figs. 2-4.

Comment 3.18

Supplementary materials, Table 2. The battery GHG emission per PKT for buses is 4.8 gCO2. Roughly, this represents (0.0048 kg CO2e * 800’000 km * 7.6 pass/vehicle)/200 kWh = 144 kg CO2e/kWh. Is this really representative of the carbon footprint of batteries? This type of information should become apparent and be validated against the rest of the literature.

Thank you for noting that this information should be apparent. We have added this value to Table 5. The bus batteries were modeled after an NMC622 chemistry (80 kg-CO_{2e} per kWh), which has a slightly higher GHG intensity than the LFP batteries (79 kg-CO_{2e} per kWh) used in light-duty vehicles. Notably, one battery replacement is modeled, resulting in a total battery lifetime of 440,500 VKT.

Comment 3.19

Supplementary materials, Table 3. Some reductions in terms of GHG emissions are striking, to say the least. For example, for intercity rail, it goes from 56 gCO2/PKT to 0.26 (effectively, a 215-reduction factor). Is this really correct? If the electricity is that much greener in the future, does it really include lifecycle emissions (i.e., emissions from building wind turbines, solar PV, etc.), or are those only direct emissions from the power plants? Please add in the parameters table I asked you to insert the GHG emission intensity per kWh (or per MJ).

Thank you for noting that the GHG emissions intensity was lower than expected. We have corrected the GHG emissions intensity value in GREET to include the emissions from building electricity infrastructure. All values from GREET were rerun to include the updated GHG intensity. The 2023 (494 g-CO_{2e} per kWh) and 2050 (29 g-CO_{2e} per kWh) values for electricity GHG intensity are incorporated in Table 5.

Reviewer #1 (Remarks to the Author):

Thanks for addressing my comments. I have no further questions.

We thank the reviewer for their diligent review.

Reviewer #3 (Remarks to the Author):

While I do not necessarily agree with all the assumptions and values used in this study, the authors have made the necessary efforts to present them transparently to the readers. Also, adding the Monte Carlo and sensitivity analyses adds previously missing information. This effort is very welcome.

Hence, I think the study is comprehensive and of good quality.

However, I still fail to see the novelty of the work. If we summarize the findings:

- Battery systems's relative carbon footprint will increase by 2050 as the energy system decarbonizes.
- Shifting away from light-duty vehicles can achieve near-term GHG reductions.
- And the greatest emissions reduction is achieved by switching to decarbonized power.

I may lack perspective on this topic, but I assume most readers have known about this already.

We thank the reviewer for their careful review of the manuscript. In response to clarifying the novelty and contributions of the study, we have added the following sentence to the last paragraph of the introduction:

“Overall, this study provides benchmark values for average GHG emissions of United States transportation technologies and projected advancements nationwide, enabling comprehensive emissions comparisons across scenarios to guide technology development and adoption efforts.”