

Response to Reviewers

Reviewer #2

This pioneering study reveals unexpectedly high VOC emissions from vehicles on the Tibetan Plateau, with evaporative sources dominating due to low-pressure enhancement—novel and rigorously validated findings. The experimental design (multi-tunnel mobile measurements) and analytical rigor (PMF/NNLS source apportionment) are exceptional. While the proposal for electric vehicle (EV) adoption in Tibet offers a promising pathway for emission reduction, it overlooks severe battery efficiency decay in low-temperature high-altitude environments, weakening policy relevance. I recommend softening the emphasis on this aspect.

Reply: We sincerely thank you for taking the time to review our paper. In the following, we address your comments point by point and revise the manuscript accordingly. For clarity, we list the original comments below in *black italics*, and our responses and changes in the manuscript in blue and red, respectively.

We agree that low temperatures and high-altitude conditions can negatively impact battery performance, including reduced mileage range, charging inefficiency, and cold-start limitations. These environmental constraints could affect the practicality of EV deployment in the Tibetan Plateau. In response, we have revised the section 3.5 to acknowledge these challenges while maintaining a balanced policy outlook. We have also removed the recommendation for large-scale EV adoption from the Abstract. Revised paragraph in section 3.5 Implications and perspectives: (Line 287-295).

One promising approach for Tibet is the strategic promotion of electric vehicles (EVs), supported by China's mature EVs industry and Tibet's abundant renewable energy resources. The region's installed capacity of hydropower and solar energy exceeds 10 million kilowatts (National Energy Administration, 2024), with ongoing development of large-scale solar and wind projects. However, local electricity demand remains low due to sparse population and limited industry, resulting in surplus energy transmitted eastward via the 'West-East Electricity Transmission' project (Xinhua News Agency, 2024). Promoting EVs could absorb this surplus, alleviating grid strain. Despite this,

the deployment of EVs in Tibet faces specific challenges, particularly due to the region's low-temperature environments. These conditions necessitate advancements in battery technology, such as the development of solid-state batteries with improved thermal resilience, as well as altitude-adaptive battery management systems.

Specific comments:

1. Line 38-39: This study emphasizes the importance of non-tailpipe emissions such as evaporative emissions. Therefore, it is necessary to add some descriptions about non-tailpipe emissions. Do non-tailpipe emissions only include the evaporation of fuel and solvents? Furthermore, what does "solvents" refer to? Is it windshield wiper fluid, or automotive surface/interior coatings? How are they emitted? Are they emitted intentionally by humans, or are they continuously emitted like fuel? The literature support provided here may not be sufficient.

Reply: Thank you for raising this important point. In our study, “non-tailpipe emissions” specifically refer to evaporative emissions related to fuels and fuel-related additives, which are continuously or intermittently released through mechanisms such as running loss (during engine operation), hot soak (after engine shutdown), permeation, and diurnal breathing. In this context, “solvents” primarily refer to low-volatility hydrocarbons blended into fuel formulations, rather than materials like windshield washer fluids or interior coatings.

To address this ambiguity, we have revised the relevant paragraph in the Introduction to clarify the scope of non-tailpipe emissions, define what is meant by “solvents,” and explain how such emissions occur. We have also added additional literature references to support this clarification. The revised sentence is as follows: (Line 37-40)

“The former refers to gases emitted from engine systems due to incomplete combustion or unburned fuel (Zhang et al., 2024), while the latter mainly consists of evaporative emissions from fuels and fuel-related additives, released through processes

such as running loss, hot soak, permeation, and diurnal breathing (Zhang et al., 2024; Pierson et al., 1999; Yue et al., 2017; Man et al., 2020; Liu et al., 2015; Harrison et al., 2021).”

2. Line 50: Do the terms Qinghai-Tibet plateau and Tibetan Plateau used in this article convey the same meaning or are there any differences between them?

Reply: Thank you for pointing this out. The terms “Qinghai-Tibet Plateau” and “Tibetan Plateau” are commonly used interchangeably in the literature and refer to the same geographical region. However, to avoid confusion and maintain consistency throughout the manuscript, we have unified the terminology and now consistently use “Tibetan Plateau” in the revised version of the manuscript.

3. Line 53-56 This part seems more like a statement of conclusion, and it is not recommended to place it in section 1 Introduction. It is suggested to revise it.

Reply: Thank you for your constructive suggestion. We agree that the sentences in Lines 53–56 are more suitable for the Results and Discussions or Conclusion sections, rather than the Introduction. Accordingly, we have revised this part of the text to avoid making definitive conclusions too early. The revised paragraph now focuses on the motivation and objectives of the study, while the findings are reserved for later sections.

The revised text in introduction (Line 53–58):

“Within the framework of the second scientific expedition and research program of the Tibetan Plateau (STEP) (Yao et al., 2012; Ye et al., 2023), we conducted vehicular emission measurements in 10 tunnels across the Tibetan Plateau, spanning an altitude range of nearly 3000 m. This unique natural setting enabled us to investigate how vehicular emission characteristics respond to changing elevation, with a particular emphasis on the role of low atmospheric pressure. The study aims to enhance the current understanding of VOC emissions from vehicles in high altitude regions, which remain poorly characterized in existing literature.”

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90 *4. Line 60 and many others: Either use Table x / Figure x or Tab. x / Fig. x. Unify*
91 *throughout the manuscript according the journal's format requirements.*

92 Reply: We have modified it according to the journal format requirements and
93 unified the format throughout the paper.

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95 *5. Line 73: This statement states that analysis will be conducted a week after sampling.*
96 *Considering that the entire mobile observation spans a long distance, how many days*
97 *did the sampling last, and are all samples taken at the same time in the same tunnel?*

98 Reply: Thank you for your insightful question. During the mobile measurements,
99 which covered a total distance of approximately 2000 km across the Tibetan Plateau,
100 sampling was not conducted simultaneously in all tunnels; instead, it was performed
101 sequentially over 10 days. Following sample collection, all VOC canisters were
102 transported from Tibet to our laboratory in Guangzhou, a process that took
103 approximately one week. We initiated the GC-FID/MS analysis immediately upon
104 receipt of the samples, ensuring that all samples were analyzed within one week. To
105 enhance clarity in the manuscript, we have revised the relevant sentence in Section 2.2,
106 and add more descriptions in SI Text 1 about the test.

107 Section 2.2 Line 75-78: The online instruments were pre-calibrated to minimize random
108 errors. The VOC samples, collected over a 10-day sampling campaign across multiple
109 tunnels, were analyzed within one week after transportation to our laboratory using a
110 gas chromatography-flame ionization detection/mass spectrometry (GC-FID/MS)
111 system (Text S1), ensuring minimal pre-analysis storage time.

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113 SI Text 1 Line 27-32: “Sampling was conducted over a 10-day period, during which we
114 covered a distance of approximately 2000 km. The samples were collected at various
115 tunnels along the route, and to minimize the effects of external variables, each tunnel
116 was tested in both directions over 4–6 rounds, with a 2-hour window for each test. After
117 completing the sampling, the samples were transported to our laboratory in

approximately one week before commencing the analysis.”

6. Line 74-75: *The piston effect is generally aimed at vehicles traveling in the same direction within the same tunnel. The author mentioned sampling at the rear of the tunnel. Has this study measured tunnels with vehicles traveling in both directions simultaneously? If so, how are these types of tunnels sampled? In addition, please also check the correctness of the references cited in the literature (Chung and Chung, 2007).*

Reply: Thank you for this insightful question. Yes, among the 46 valid samples in our study, three canisters were collected in tunnels with vehicles traveling simultaneously in both directions (bidirectional tunnels). For these specific cases, we adjusted our sampling strategy by collecting air samples at the midpoint of the tunnel rather than at the rear, in order to reduce the interference caused by opposing airflows and ensure a representative mixture of emissions from both directions. This midpoint sampling strategy helps to minimize spatial gradients and turbulence near the entrances and exits, as recommended by prior tunnel sampling protocols.

We have revised the Materials and Methods section to clearly describe this adjustment in our sampling strategy. The revised paragraph is as follows (Line 78-85):

In the one-way tunnels, the online data (i.e., CO₂ and CO) showed a noticeable piston effect (Fig. S3) (Chung and Chung, 2007), with concentrations gradually increasing towards the end of the tunnel. The air at the tunnel’s tail end was assumed to represent a well-mixed plume from emissions of all vehicles in the tunnel (Hwang et al., 2023; Gillies et al., 2001). Therefore, in these tunnels, offline sampling was initiated in the rear section and lasted approximately 1 minute to capture the accumulated air masses. Additionally, three tunnels in our study had bidirectional traffic, where the piston effect was less pronounced due to opposing flows. For these cases, sampling was conducted at the tunnel midpoint to ensure representative mixing of emissions from both directions. Background concentrations of VOCs were determined at the Yangbajing background site during the same field campaign of STEP (July-August, 2022) (Tao et al., 2024).

Regarding the reference to Chung and Chung (2007), we have re-checked the citation and confirm that it correctly refers to a study that includes modeling and discussion of pollutant dispersion mechanisms in traffic tunnels, including the piston effect. The citation has also been double-checked for accuracy and relevance.

7. Line 119-122: *When comparing plateau vs. plain EF/ER, the authors selected only two tunnel examples (Hong Kong 50m and Taiwan 330m). Please include additional examples to enhance representativeness.*

Reply: Thank you for this valuable suggestion. We fully agree that including more low-altitude tunnel studies would enhance the representativeness of the comparison. However, the calculation of emission factors (EF) and emission ratios (ER) in our study relies not only on speciated VOCs data, but also requires corresponding CO and CO₂ measurements to normalize emissions relative to fuel combustion. To date, we were only able to identify two published tunnel studies (Shing Mun Tunnel in Hong Kong and Chung-Liao Tunnel in Taiwan) that provide all the necessary co-measured data (VOCs, CO, and CO₂) in a format that allows consistent EF/ER calculations. Unfortunately, other tunnel studies either do not include CO/CO₂ data or do not report them in sufficient detail for this purpose.

8. Line 137: *Inconsistent spacing around “±” symbols.*

Reply: We have modified in the revised manuscript.

9. Line 137: *Replacing "contributing to" with "accounting for".*

Reply: We have replaced "contributing to" with "accounting for".

References:

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