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Smart & Resilient Logistics Corridors Future Gateway to the Green Trade

PASSENGER TRANSPORTATION EMISSION: TRENDS AND PROJECTIONS TILL 2050

Martin Fale(1) and Matevž Obrecht(1)

University of Maribor, Faculty of Logistics, Mariborska cesta 7, Celje, Slovenia

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ABSTRACT

The environmental aspect of transportation mode choice has become an increasingly significant factor in individual's behaviour. By utilizing historical and current emissions data, it is possible to project future emission trends, which can be used for transport policies at both micro and macro levels. Emission factors are commonly used in studies addressing greenhouse gas emissions and decarbonization strategies. The research aimed to explore the projected trends in emissions from various transportation modes up to 2050. Based on the slope of the trendline of the scatter plot, we were able to determine whether the trend indicates an increase or decrease in emissions for each transportation mode. In first scenario, analysis of emissions data from the years 2018, 2019, 2021, 2022, 2023, and 2024, indicates that emissions will rise across all transportation modes, except for trains, which are projected to achieve zero-emission operation after 2040. Among the other transportation modes, emissions from ships are expected to increase the fastest, followed by cars, airplanes, and motorcycles, with buses exhibiting the slowest growth. The results of the applied method deviate from the expected emission trend, presented in the second scenario, which predicted a decrease in emissions. This raises the question of the challenges in predicting future emission trends and highlights the need to develop mathematical models that account for both the current state and the uncertainty of future developments in decision-making.

1. INTRODUCTION

The decision on the choice of transportation mode to travel is mostly related to the comparison between the time spent and the expected costs. The trend to reduce the negative environmental impact of transportation has raised awareness about the environmental component of travel - to what extent the chosen transportation mode negatively affects the environment. Emissions factors are frequently used in various applications and studies addressing greenhouse gas emissions in transport (Charly & Caulfield, 2025; Olivari et al., 2025) and potential solutions for decarbonization (Yu et al., 2020). This topic is crucial for policymakers, as the transport sector is key to the economy, and the use of reliable emissions factors forms the foundation for developing effective decarbonization strategies at global, national, and local levels. Emissions factors are often grouped by transportation mode, despite significant variations within each transportation mode in terms of technology, route length, energy source, and other factors (Noussan et al., 2023). In their study, Noussan et al. highlighted the importance of raising awareness about the complexity of selecting the appropriate set of emissions factors and the significance of incorporating variability and uncertainty, which are crucial for improving the effectiveness of innovative mobility strategies. They presented emissions factors within the framework of life-cycle analysis for various transportation modes of passenger transportation.

The negative environmental impacts caused by various transportation modes during their operation can be monitored through exhaust emissions, particularly CO_2 emissions per passenger kilometre. There is a noticeable variation in the way exhaust emissions are presented - either as a total for a specific type of transportation or based on the distance travelled (IEA, 2020). The challenging part is that data on total emissions from the transportation sector in megatons cannot be used in calculations related to a specific type of transportation. During our research, inconsistencies were noticed in the units used to present transportation emission data, which must be considered in further studies. It is important to avoid comparing emissions without accounting for differences in units or normalization approaches (IEA, 2019, in Rodrigue, 2024).

Additionally, there are differences in how transportation modes are categorized - especially when distinguishing between diverse types of flights. The challenge lies in the difficulty of determining exhaust emissions for a particular transportation mode. Current research has focused on estimating emissions within a specific area, as transportation emissions are geographically conditioned. Shen et al. (2020) used data on emissions factors for cars and buses, obtained from the studies by Hu (2017) and Yu et al. (2016), which determined the emission values for cars and buses specifically for the city of Nanjing. This data was applied in their research on transportation mode choices among young people in Nanjing, particularly to highlight the negative effects of increased travel distances in the city due to a potential rise in the use of e-hailing services.

We identified a notable research gap: existing studies lack standardized and comprehensive emission data that would enable direct application in modelling processes across various problem settings. Moreover, data used in public statements and announcements may be misleading, particularly regarding emissions per passenger-kilometre for specific transportation modes, potentially affecting strategic decision-making in the development of the transportation sector. This study addresses the following research question: How will emissions from different transportation modes change by 2050, irrespective of geographical or demographic constraints?

2. LITERATURE REVIEW

Existing research covers a wide range of decision-making parameters, with travel time and travel cost being the most used. However, an increasing number of studies incorporate additional factors into models to better reflect real-world conditions, leading to more accurate and tangible results. The environmental aspect in modelling transportation mode choice is present in some studies.

Asgarpour et al. (2024) focused on freight transport, comparing rail, road, and inland waterways. Their study explored the preference levels for each mode by analysing pairwise variations of key variables, which were selected based on three decision-making strategies: cost-oriented, time-oriented, and environment-oriented. In particular, the environment-oriented strategy highlighted CO_2 emissions and transport costs as critical factors. The results emphasized that road transportation is the least favoured option due to its high emissions and costs, whereas rail and inland waterway transportation stand out as more sustainable and competitive alternatives when environmental impact is prioritized in decision-making.

The study by Chen and He (2023) examined individuals' preferences regarding the use of mobility-as-a-service (MaaS) in the context of Taipei city. Participants in the study were classified into three groups - MaaS supporters, MaaS sceptics, and MaaS enthusiasts - based on their attitude toward mobility, specifically their intermodal tendencies, willingness to be a green traveller, and car independence. The concept of "willingness to be a green traveller" was derived from the results of a mathematical model, which incorporated responses from a survey questionnaire.

You et al. (2020) determined the carbon footprint of an individual traveling by subway in Nanjing. They used data collected through smart cards in the transportation system. Based on the travel distance, they calculated emissions per individual while tracking the total personal distance travelled, as the use of smart cards allows for monitoring everyone’s route. This enabled them to accurately calculate the daily emissions associated with an individual's subway travel.

Viri and Tiikkaja (2025) presented a data-driven approach to calculate the carbon emissions per kilometre in Finland. They achieved this by combining data from the Finnish vehicle fleet and the Finnish National Travel Survey, which contains information about the travel habits of the Finnish population. The study determined emissions for cars, taxis, local public transport, and long-distance transport.

De Bortoli and Feraille (2024) examine the sustainability of long-distance mobility, the decarbonization effect of high-speed rail (HSR), and the ban on short-haul flights, which are current topics of discussion in Europe. However, comprehensive environmental assessments in these areas are rare. As part of their study, they conducted a life-cycle analysis (LCA) to compare different transport options on the Paris-Bordeaux route in France: HSR, airplane, bus, personal car, and carpooling. Based on four environmental indicators, the general ranking of transport options, from best to worst, is as follows: bus, HSR, carpooling, personal car, and airplane. The results of the study support the overall implementation of short-haul flight bans and investments in HSR infrastructure. Additionally, they calculated that electric HSR solutions emit between 33 and 120 g CO_2 per passenger kilometre, depending on the energy mix used and vehicle occupancy, enabling international comparisons of transportation emissions.

Smit and Boutler (2024a) examined the potential transition from road to rail transport to reduce emissions by 2030 and 2050, using a case study of passenger and freight transport between Brisbane and Melbourne. The analysis provides data on passenger transportation emission intensities, measured in grams per passenger-kilometre. For both road and electric rail passenger transport, a general improvement in emission intensity over time was predicted, with the lowest values expected by 2050. However, significant differences were observed between the transportation modes. Compared to the emissions intensity of 2019, long-term reductions were predicted to be greater for electric rail transportation (67% reduction in 2030 and 82% reduction in 2050) than for road transportation (4% increase in 2030 and 57% reduction in 2050). The 4% increase in emissions intensity of road passenger vehicles between 2019 and 2030 reflects the continued growth of heavier vehicles in the fleet (e.g., SUVs and light trucks), leading to higher average vehicle weight, resulting in increased energy consumption and emissions. In their subsequent study, Smit and Boutler (2024b) extended the analysis to include maritime freight transport and both passenger and freight air transport. For passenger air travel, they projected a potential reduction in emission intensity from 166 g CO_2 per passenger-kilometre in 2019 to 89 g CO_2 per passenger-kilometre by 2050. The forecasts for Road, Rail, and Air transportation modes, as presented in the study by Smit and Boutler (2024b), are shown in Figure 1.

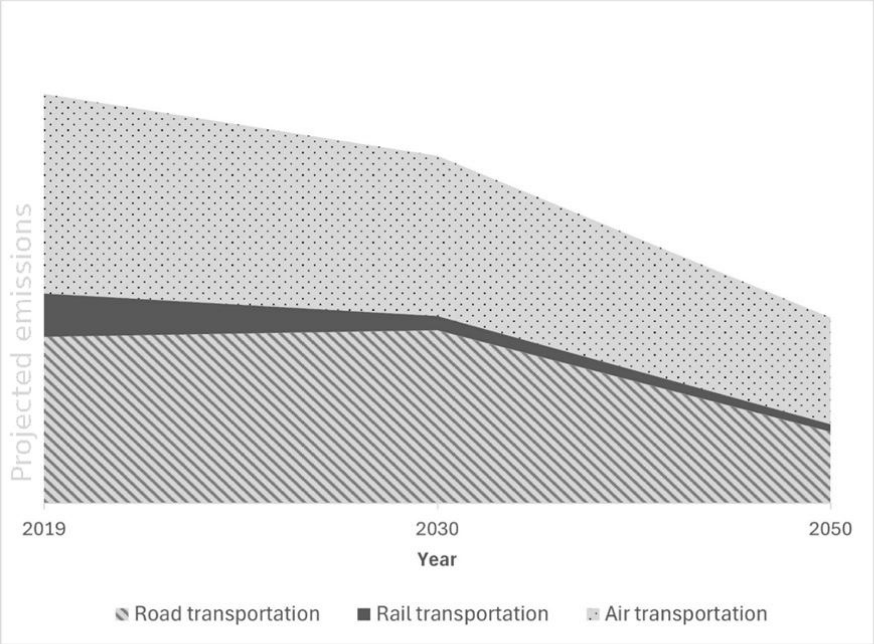

Figure 1: Projected CO_2 emissions per passenger-kilometre through 2050, according to the study by Smit and Boutler

3. METHODOLOGY

For the purposes of this study, it was necessary to identify related research to present the problem's context and to gather data on emissions. The search for related studies was conducted through the ScienceDirect and Web of Science databases. In the search process, keywords "carbon footprint AND transportation mode", "emissions per kilometre AND transportation mode", and "emissions per passenger kilometre AND transportation mode" were employed.

The research will consider CO_2 emissions expressed as passenger-kilometre equivalents. We considered data on emissions per passenger kilometre, with data available for the years 2018, 2019, 2021, 2022, 2023, and 2024. The data are derived from a range of international sources and include the UK Government - Department for Energy Security and Net Zero, Our World in Data, the International Council on Clean Transportation, Visual Capitalist, the Federal Environment Agency, the Bureau of Transportation Statistics, the UK Department for Business, Energy & Industrial Strategy (via Our World in Data), GreenMatch, the National Transport Commission, Lufthansa Innovation Hub Analysis, and TMNT.com. The sources classified emissions for 47 diverse types of transportation. The analysis included a wide range of transportation modes, encompassing public, private, and air-based travel. The data were consolidated based on the primary transportation mode, namely bus, car, bicycle, ship, airplane, motorcycle, and train. The final classification is presented in Table 1 (Open Transport, 2020; Reimer, 2021; Bhutada, 2022; Comer, 2022; Congressional Budget Office, 2022; Wendering, 2022; Burgees, 2023; Ritchie, 2023; Schunck, 2024; Transform Scotland, 2024; Ukpanah, 2024; Visual Capitalist, 2024).

Table 1: Classification of types of transportation by transportation mode

Transportation mode	Type of transportation mode considered
Airplane	General air travel, domestic flights, and categorized flights based on distance: short-haul, medium-haul, and long-haul flights
Bicycle	E-bikes and bicycles
Car	Petrol cars with four passengers, plug-in hybrid cars, two-seater cars, electric cars, hybrid cars, diesel cars, gasoline cars, regular taxis, personal vehicles, and carpooling

Motorcycle	Gasoline-powered scooters and motorbikes, electric kick-scooters (dockless), e-scooters
Ship	Ferries (categorized as foot passenger, car passenger, and short-distance ferry travel < 200 km), as well as cruise ships
Train	Eurostar (international rail), light rail systems (both overhead and underground), national rail, regional trains, high-speed trains, electric trains, diesel-powered trains, transit rail, trams, and general passenger railroad services

The average values of all available emission data were considered for each transportation mode. Using Microsoft Excel, the average values were visualized using a scatter plot, while a scatter plot trendline was employed to project future emission estimates for the years 2030, 2035, 2040, 2045, and 2050. Each scatter plot trendline was generated using actual CO_2 emission data from the years 2018, 2019, 2021, 2022, 2023, and 2024. Based on the slope of the trendline, it was possible to identify whether the trend indicates an increase or decrease in emissions by 2050, and for each transportation mode, how fast emissions are rising or falling compared to other transportation modes. The obtained results were analysed and discussed.

4. RESULTS

Scenario 1 illustrates the trend in emissions based on data from the years 2018, 2019, 2021, 2022, 2023, and 2024. Scenario 2 builds on this by incorporating projections from Smit and Boutler (2024b) into the dataset.

169 emission data points on CO_2 emissions per passenger-kilometre were collected. The average values are presented in Table 2 (Open Transport, 2020; Reimer, 2021; Bhutada, 2022; Comer, 2022; Congressional Budget Office, 2022; Wendering, 2022; Burgees, 2023; Ritchie, 2023; Schunck, 2024; Transform Scotland, 2024; Ukpanah, 2024; Visual Capitalist, 2024).

Table 2: Average values of CO_2 emissions per passenger-kilometre by transportation mode

CO_2/p km	2018	2019	2021	2022	2023	2024
Bus	66.5	27	63.9	80.8	17.7	75.8
Car	128.7	n. a.	168.2	118.7	191.6	135.2
Bicycle	n. a.	n. a.	15.6	n. a.	6	n. a.
Ship	74.5	n. a.	151.5	111.4	n. a.	100.2
Airplane	187	n. a.	183.4	183.3	n. a.	207.1
Motorbike	103	n. a.	110	110	119.6	113.6
Train	23.5	51	64.5	25.8	24.6	30

It should be noted that there is a significant variation in emission data points across different transportation modes. For example, battery electric vehicles lower the average emissions of cars, while petrol- and diesel-powered variants increase them. For easier illustration, the minimum and maximum emission values for the transportation mode Car, included in our study, are presented in Table 3. Also, when dealing with emission data, it is important to highlight the measurement method, particularly from the perspective of the number of passengers or the occupancy rate of the transport vehicle.

Table 3: Presentation of minimum and maximum values of emission values for the transportation mode Car, by year, in CO_2 emissions expressed as passenger-kilometre

Year	Minimum CO_2 emissions per passenger kilometre and type	Maximum CO_2 emissions per passenger kilometre and type
2018	48; Petrol car (4 passengers)	212; Regular Taxi
2021	132.47; Personal Vehicle	288.32; Personal Vehicle
2022	47; Car (Electric)	173; Car (Diesel)
2023	121.9; Carpooling	243.8; Personal Vehicle
2024	47; Car (Electric)	208.1; Regular Taxi

Values in Table 2 were entries for data simulation, where a scattered plot was used for visualization. The mode Bicycle was not included as only two emission data points were available for from the years 2018, 2019, 2021, 2022, 2023, and 2024. A trendline was then added to the chart, enabling us to obtain the equation of the trendline, which was subsequently used for forecasting. The following six equations, numbered 1 through 6, were derived (x denotes the year):

$$\text{Bus} = 1{,}2967 \cdot x - 2565{,}5 \tag{1}$$

$$\text{Car} = 3{,}5794 \cdot x - 7087{,}7 \tag{2}$$

$$\text{Ship} = 4{,}2206 \cdot x - 8421{,}4 \tag{3}$$

$$\text{Airplane} = 2{,}488 \cdot x - 5567{,}9 \tag{4}$$

$$\text{Motorbike} = 2{,}2315 \cdot x - 4400 \tag{5}$$

$$\text{Train} = -1{,}6392 \cdot x + 3349{,}5 \tag{6}$$

Based on these equations, we calculated the projected values for the years 2030, 2035, 2040, 2045, and 2050. We then combined the emission data collected during the research with the extrapolated values. The combined dataset is presented in Figure 2.

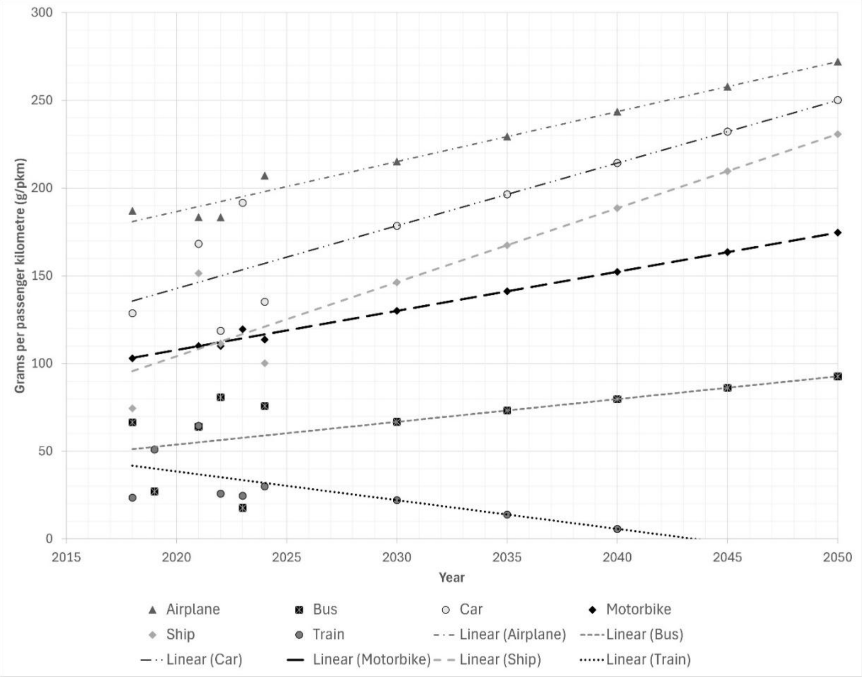

Figure 2: Projection of emission trends for selected transportation modes until 2050

In addition to the dataset used for Figure 2, Figure 3 also includes the forecasts from Smit and Boutler (2024b). We included values for road, rail, and air transportation. The base year was 2019, and forecasts were included for the years 2030 and 2050. The following three equations, numbered 7 through 9, were derived (x denotes the year):

$$\text{Road transportation} = -2{,}7451 \cdot x + 5694{,}1 \tag{7}$$

$$\text{Rail transportation} = -0{,}8723 \cdot x + 1791{,}5 \tag{8}$$

$$\text{Air transportation} = -2{,}4528 \cdot x + 5115{,}5 \tag{9}$$

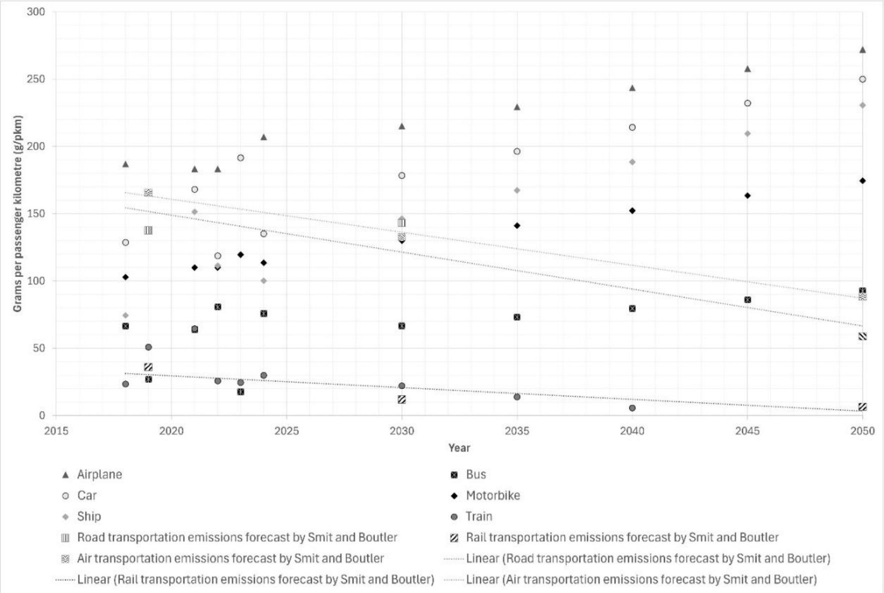

Figure 3: Projection of emission trends for selected modes of transportation until 2050 with additional forecast by Smit and Boutler

5. DISCUSSION

The emissions of selected transportation modes were forecasted up to 2050. Figure 2 shows that, based on emission data from the years 2018, 2019, 2021, 2022, 2023, and 2024, emissions are projected to increase across all transportation modes, except for transportation mode Train. According to the applied model, the Train transportation mode is expected to achieve zero-emission operation after 2040, which may also be related to the decarbonisation of electrical energy, projected for the same period. Among other transportation modes, emissions will increase the fastest in the case of transportation mode Ship, followed by transportation mode Car, then Airplane and Motorcycle, and the slowest increase will be observed in the case of transportation mode Bus.

The projected emission trend for transportation mode Rail corresponds with the findings of Smit and Boutler (2024a), who forecast a substantial reduction in rail-related emissions by 2050. According to our model, transportation mode Rail achieves zero-emission status after 2040. In the case of road transportation modes such as cars, buses, and motorcycles, the observed trends align with Smit and Butler's projections up until approximately 2030, which anticipate an increase in emissions. However, in contrast to their projected gradual decline beyond 2030, our model suggests a continued upward trend in emissions from these modes through to 2050. For the transportation mode airplane, unlike the study by Smit and Butler (2024b), our model does not project any reduction in emissions at all.

The issue is that Figure 2 suggests highly unlikely emission trends. Total transportation-related emissions are expected to decrease over time, making the scenario shown in Figure 2 highly unlikely. Figure 3, which includes additional forecasts for emissions in 2030 and 2050, illustrates the range between our predictions for Road and Air transportation modes and the projections by Smit and Boutler (2024b). The latter more accurately reflect the expected emission trends for transportation modes by 2050. This discrepancy can be attributed to the method used, which is based on a scattered plot. Since the predictions rely solely on historical data and disregard any potential changes beyond the final year of observation, they omit critical factors that are likely to influence future emissions, such as technological advancements and evolving regulatory frameworks. Similar or comparable results would be obtained with any forecasting model that relies purely on historical data. Adjustments like weighting recent data more heavily than older data might slightly alter the predicted trend, but such models still fail to account for future developments. Smit and Boutler (2024a; 2024b) also highlight the issue of prediction accuracy due to the broad range within which future emissions are expected to fluctuate. This underlines the need to develop a mathematical model that incorporates both the current state and the uncertainty introduced by technological progress and anticipated policy changes. Technological innovation or legislative shifts could significantly alter emission trajectories, potentially causing major deviations from forecasts based solely on past trends.

We should not conclude, based solely on these trends, that the lack of reduction in greenhouse gas emissions is due to insufficient technological progress or a weak environmental regulatory framework. Instead, it is important to also consider the increased demand for mobility. The more we travel, the more emissions are produced. It is possible that technological advancements or proposed changes in legislation are not keeping pace with the growing demand for mobility.

6. CONCLUSIONS

The environmental aspect of modelling transportation mode choice is becoming an increasingly important variable in individual behaviour. Based on historical and current emissions data, it is possible to develop projections of future emission trends. These projections can support the formulation of transport policies at the micro level, such as individual decisions regarding transportation modes for urban travel, as well as at the macro level, including travel between countries or continents.

The main limitation of the study lies in the use of a scattered plot method, which relies solely on historical data and fails to account for future changes such as technological advancements or regulatory developments that could significantly impact transportation emissions. Other limitation of the study lies in the approach used to determine average values, as calculated overall averages have shown by including all gathered data within each transportation mode category. Also, the study relied exclusively on secondary data. The practical value of the research could have been further enhanced had we conducted our own calculations based on primary, real-world data. At this point, it is important to highlight another limitation of the study, namely, the limited availability of relevant and reliable data sources. It was observed that some datasets are duplicated across multiple websites, which reflects a broader issue: the scarcity of original, transparent emission calculations that are suitable for research purposes.

It is important to note that our analysis has focused solely on emissions occurring during the operational phase of transportation modes. Emissions associated with the production and construction of the transportation mode, those related to the provision of the energy source for its operation, as well as emissions resulting from its disposal or decommissioning at the end of its lifecycle, have not been comprehensively considered, as done in the study by de Bortoli and Feraille (2024).

For further research in this field, the availability of accurate and detailed data is essential for effective modelling. We suggest the development of methods for monitoring emissions from different transportation modes based on the collection of data on distance travelled between service cycles or technical inspections. By linking the travelled distance to a specific type (e.g., car) and subtype (e.g., SUV) of transportation mode, emissions associated with that transportation mode can be more accurately determined.

The relevance of studies like this lies in their potential to provide researchers with emission data that can be incorporated into the environmental dimension of transportation mode choice modelling, enhancing both the accuracy and applicability of such models. This data can support policymakers in developing sustainable transport strategies and assist individuals in selecting environmentally friendly transportation options.

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8. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES:

During the preparation of this work, the author(s) used Chat GPT in order to proofread the text. After using this tool/service, the author(s) reviewed and edited the content as necessary and take(s) full responsibility for the content of the publication.