

Research Article

Modeling Vehicle Number Change and Carbon Footprint Trends in Turkey (2030–2040) Using Polynomial RegressionHüseyin SÖYLER^{1*}, Ahmet KARAOĞLU²¹Gerze Vocational School, Sinop University, Sinop, Türkiye²Department of Computer Engineering, Sinop University, Sinop, Türkiye*Correspondence: hsoyler@sinop.edu.tr

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Abstract: This study analyses the historical evolution of vehicle types in Turkey between 2004 and 2024 and projects transport-related carbon emissions through 2040 under three distinct policy scenarios: the Usual Fossil-Fuel Scenario (UFFS), the Moderate Sustainability Policy Scenario (MSPS), and the Advanced Sustainability Policy Scenario (ASPS). Using official data, future vehicle fleet composition was forecasted by fuel type, and corresponding carbon footprints were calculated based on emission coefficients. Results show that under the UFFS, emissions are expected to rise significantly, surpassing 32 million tons of CO₂ by 2040. Conversely, the ASPS scenario demonstrates the potential to reduce emissions by more than 30% compared to 2024 levels. The study highlights the need for strong policy interventions such as widespread electrification, fossil fuel phase-out strategies, and integrated transport-energy planning to align with Turkey's 2053 Net Zero Emission Target.

Keywords: Sustainable transportation, carbon footprint, electric vehicles, time series analysis, Polynomial Regression model, Turkey transportation sector.

Türkiye’de 2030–2040 Arasında Araç Sayısı Değişimi ile Karbon Ayak İzi Eğilimlerinin Polinom Regresyon ile Modellenmesi

Özet: Bu çalışma, Türkiye’deki araç türlerinin 2004–2024 yılları arasındaki tarihsel değişimini inceleyerek, ulaştırma sektörüne bağlı karbon emisyonlarının 2040 yılına kadar üç farklı politika senaryosu altında nasıl şekilleneceğini projekte etmektedir: Mevcut Fosil Yakıt Senaryosu (UFFS), Orta Düzey Sürdürülebilirlik Politikası Senaryosu (MSPS) ve Gelişmiş Sürdürülebilirlik Politikası Senaryosu (ASPS). Resmî verilere dayanılarak yakıt türüne göre araç filosunun gelecekteki dağılımı tahmin edilmiş ve bu dağılıma karşılık gelen karbon ayak izi, emisyon katsayıları kullanılarak hesaplanmıştır. Bulgular, UFFS senaryosunda emisyonların önemli ölçüde artarak 2040 yılında 32 milyon tonu aşabileceğini göstermektedir. Öte yandan, ASPS senaryosu kapsamında emisyonların 2024 seviyesine göre %30’dan fazla azaltılabileceği ortaya konmuştur. Çalışma, Türkiye’nin 2053 Net Sıfır Emisyon Hedefi doğrultusunda güçlü politika müdahaleleri, elektrikli araçların yaygınlaştırılması ve ulaştırma-enerji entegrasyonunun gerekliliğini vurgulamaktadır.

Anahtar kelimeler: Sürdürülebilir ulaşım, karbon ayak izi, elektrikli araçlar, zaman serisi analizi, Polinom Regresyon modeli, Türkiye ulaşım sektörü.

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1. Introduction

Climate change poses significant threats to transportation infrastructure and contributes to increasing greenhouse gas (GHG) emissions. The transport sector, particularly road transportation, is a major source of GHG emissions (Güzel & Alp, 2020). To address these challenges, adaptation measures for road, rail, air, and water transportation have been proposed to enhance resilience against extreme weather events and natural hazards (Stamos et al., 2015). These measures include strategies to minimize impacts on road infrastructure from intense precipitation and high temperatures (De Abreu et al., 2022). To reduce GHG emissions, three key strategies have been identified: improving fuel economy of passenger vehicles, advancing the use of alternative fuels like electric vehicles, and investing in public transportation (Bleviss, 2021). Modelling studies in Istanbul have shown that scenarios involving electric rail transportation, electric and hybrid cars, and emission limitations can potentially reduce GHG emissions from the transportation sector by up to 39% by 2050 (Güzel & Alp, 2020).

The transport sector significantly contributes to global carbon emissions, accounting for approximately 25% of CO₂ emissions worldwide (Ferrer & Thomé, 2023; Linton et al., 2015). Vehicles emit various greenhouse gases, including CO₂, methane (CH₄), and nitrous oxide (NO_x), through the combustion of fossil fuels (Dalianis et al., 2016). Urbanization tends to increase transport-based emissions, while technological innovation can help mitigate them (Awan et al., 2022). To address this issue, a range of modelling tools are available for analysing transport-related emissions, from microsimulation to global techno-economic models (Linton et al., 2015). Mitigation strategies include shifting to non-motorized vehicles, improving public transportation systems, and adopting green transportation technologies. However, the success of these strategies depends on context-specific factors and requires adaptation to different countries and transport modes (Awan et al., 2022; Ferrer & Thomé, 2023).

In Turkey, the transport sector is one of the largest sources of carbon emissions in terms of energy consumption, along with the industrial and residential sectors. According to TurkStat data, the number of registered vehicles in Turkey has increased significantly in the last 20 years and the carbon footprint of the transport sector has grown rapidly, especially with the widespread use of diesel-powered vehicles (*TÜİK - Veri Portalı*, t.y.). Despite the widespread use of LPG and hybrid vehicles, diesel and petrol vehicles still have a large share, making it difficult to reduce carbon emissions. However, the widespread use of electric vehicles and the increased use of renewable energy sources in the transport sector offer an important opportunity to reduce carbon emissions.

The global push towards decarbonizing the transport sector has led many countries to implement policies promoting electric vehicle (EV) adoption and infrastructure development (Zhang et al., 2014). Turkey, aiming for net-zero emissions by 2053, is focusing on electrification as a key strategy for reducing greenhouse gas emissions in its transport sector (Dönmezçelik et al., 2023). However, the country faces challenges in transitioning to sustainable road transportation, including high fossil fuel dependence and increasing energy demand. To overcome these obstacles, Turkey needs to develop comprehensive policies addressing socio-technical processes and societal contexts of change (Cevheribucak, 2021). Norway's experience with EV incentives and charging infrastructure development offers valuable lessons for other countries (Springel, 2021). Effective policies to support EV adoption should include financial incentives, technology support, and charging infrastructure development, tailored to each country's specific circumstances (Springel, 2021; Zhang et al., 2014).

Turkey's transportation sector has seen significant growth in CO₂ emissions and energy demand, driven by economic growth, population increase, and rising vehicle ownership (Isik et al., 2020). Machine learning models predict that by 2050, transportation-related energy demand and CO₂ emissions in Turkey will increase 3.4 times compared to current levels (Ağbulut, 2022). The Environmental Kuznets Curve (EKC) for Turkey does not follow an inverted U-shape, indicating a need for alternative and clean energy systems (Katircioğlu & Katircioğlu, 2018). However, technological advancements, energy efficiency improvements, and increased renewable energy adoption have shown potential in reducing CO₂ emissions (Naimoglu & Akal, 2023). To mitigate emissions, experts recommend implementing

demand management strategies for freight transportation, improving public transit systems, and providing incentives for energy-efficient vehicles and clean energy technologies (Isik et al., 2020).

Turkey's transportation sector significantly contributes to greenhouse gas emissions, accounting for 16% of the country's total emissions in 2017 (Güzel & Alp, 2020). The sector's CO₂ emissions are primarily driven by economic growth and population increase (Isik et al., 2020). Road transportation, particularly the use of conventional vehicles, is a major source of emissions (Şen et al., 2023). To address this issue, various strategies have been proposed, including the promotion of electric and hybrid vehicles, improved public transportation, and fuel efficiency measures (Güzel & Alp, 2020; Şen et al., 2023). However, the market share of electric vehicles remains low, with estimates suggesting only 0.1% by 2030 without government intervention. Policy measures such as tax incentives, government-backed loans, and increased charging infrastructure could significantly boost electric vehicle adoption (Şen et al., 2023). A holistic approach considering socio-technical processes and just energy transition is necessary for sustainable mobility in Turkey (Cevheribucak, 2021).

The analyses show that carbon emissions will continue to increase in the coming years in scenarios where the prevalence of fossil fuel vehicles continues, but the carbon footprint may decrease if the transition to electric and hybrid vehicles accelerates. Therefore, developing sustainable transport policies in Turkey, encouraging the use of electric vehicles and reducing the dependence on fossil fuel vehicles are of great importance in terms of reducing carbon emissions.

In this study, the change in registered vehicle types in Turkey between 2004 and 2024 was analysed, and a machine learning-based time series forecasting model was used to predict the number of vehicles for 2030, 2035, and 2040. Additionally, a carbon footprint analysis was conducted for the transportation sector between 2004 and 2024, and the results were compared with the projected carbon footprint estimates for 2030, 2035, and 2040 based on the predicted number of vehicles. Furthermore, the growth trend of electric and hybrid vehicles starting from 2011 was examined, and their projected evolution until 2040 was analysed. Based on these forecasts, the long-term impact of fossil fuel-powered vehicles on carbon emissions was evaluated, and the study aims to contribute to sustainable transportation policies in Turkey while emphasizing the significance of electric vehicle adoption in combating climate change.

2. Materials and methods

This study examined the changes in registered vehicle types in Turkey between 2004 and 2024 and produced projections for the years 2030, 2035, and 2040. Future trends were estimated using time series modelling techniques, specifically polynomial regression. Based on these projections, the carbon footprint of the transportation sector was calculated, and the impact of different fuel types on emissions was evaluated. Hybrid and electric vehicles were excluded from the dataset due to limited historical data and their negligible direct CO₂ emissions. Hybrid vehicles operate using both an internal combustion engine and an electric motor, thereby reducing fuel consumption, while electric vehicles rely entirely on battery power, resulting in near-zero fossil fuel use. For these reasons, only gasoline, diesel, and LPG vehicles were considered in the emission modelling process.

2.1. Data set and sources

The dataset used in this study was obtained from the Turkish Statistical Institute (TÜİK) and other official sources, and includes only the number of registered gasoline, diesel, and LPG vehicles between 2004 and 2024 (TÜİK, 2024). Due to the lack of sufficient historical data, hybrid and electric vehicles were not included in the dataset. Accordingly, the carbon emission calculations were based solely on vehicle types that rely on fossil fuels. Gasoline and diesel vehicles are powered by internal combustion engines that consume fossil fuels, while LPG vehicles utilize an alternative fuel system that results in lower carbon emissions compared to gasoline engines. The distribution of registered vehicles by fuel type and year is presented in Table 1.

Table 1. Number of Vehicles by Fuel Type (2004-2024)

Year	Gasoline	Diesel	LPG
2004	4062486	252629	793081
2005	3883101	394617	1259327
2006	3838598	583794	1522790
2007	3714973	763946	1826126
2008	3531763	947727	2214661
2009	3373875	1111822	2525449
2010	3191964	1381631	2900034
2011	3036129	1756034	3259288
2012	2929216	2101206	3569143
2013	2888610	2497209	3852336
2014	2855078	2882885	4076730
2015	2927720	3345951	4272044
2016	3031744	3803772	4439631
2017	3120407	4256305	4616842
2018	3089626	4568665	4695717
2019	3020017	4769714	4661707
2020	3201894	5014356	4810018
2021	3495172	5158803	4923275
2022	3817104	5261876	5005563
2023	4362975	5425652	5094751
2024	4908203	5541441	5172471

Changes according to vehicle types in Turkey in the years 2004-2024 are shown in Figure1.

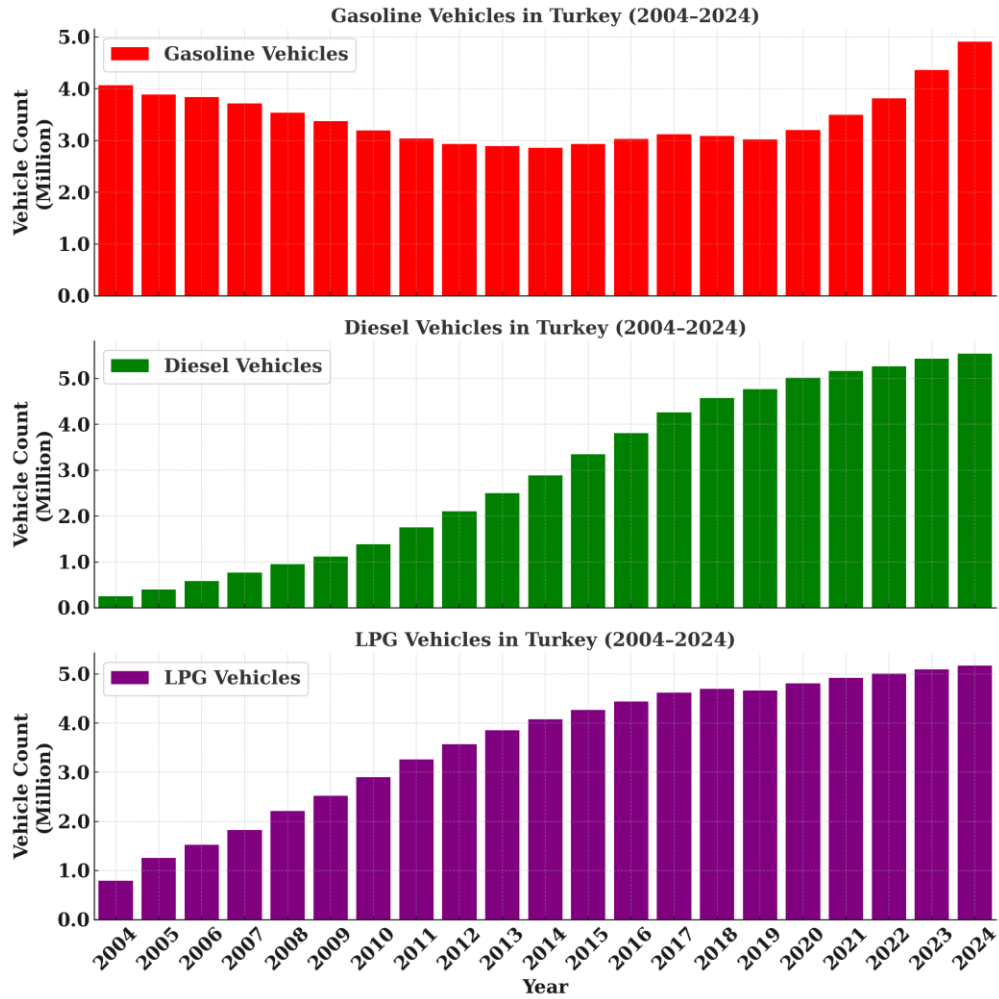


Figure 1. Change in the number of petrol, diesel and LPG vehicles in turkey in 2004-2024

2.2. Carbon emission factors

The carbon footprint calculations in this study are based on carbon emission coefficients and average annual mileage data, in line with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and national statistics from the Turkish Statistical Institute (TÜİK, 2024). The total annual emissions were estimated by multiplying the number of registered vehicles in each fuel category by their respective emission coefficient. Each emission coefficient reflects an average annual consumption of approximately 1,000 liters of fuel, corresponding to a driving distance of 10,000 kilometers per year and a mean fuel efficiency of 10 liters per 100 kilometers. The carbon intensity values per liter of fuel are approximately 2.31 kg CO₂ for gasoline, 2.68 kg CO₂ for diesel, and 1.70 kg CO₂ for LPG. When annual fuel consumption is considered, these translate into the annual per-vehicle emissions shown in Table 2.

Table 2. Carbon Emission Coefficients by Fuel Type (ton CO₂/year)

Fuel Type	Carbon Emission (ton CO ₂ /year)
Gasoline Vehicles	2.31
Diesel Vehicles	2.68
LPG Vehicles	1.70

Figure 2 shows the annual changes in transportation-related CO₂ emissions in Turkey from 2004 to 2024, disaggregated by three major fuel types: gasoline, diesel, and LPG. The area chart visually demonstrates the sharp upward trend in total carbon emissions over the 20-year period, with a rise from approximately 11.4 million tons in 2004 to 34.9 million tons in 2024 an increase of around 206%.

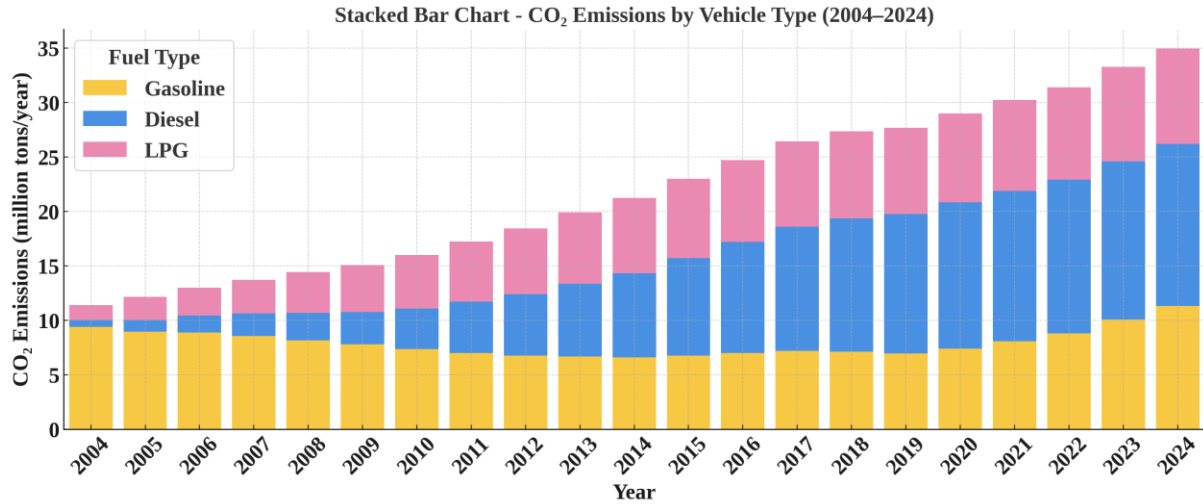


Figure 2. Carbon footprint trends by vehicle type (2004-2024)

The primary driver of this increase is the rapid expansion of the diesel vehicle fleet, particularly after 2010. Diesel-related emissions soared from just 0.68 million tons in 2004 to 14.85 million tons in 2024, increasing their share of total transport emissions from 6% to 42%. A pivotal turning point occurred in 2013, when diesel emissions surpassed those from gasoline-powered vehicles, marking a significant shift in the composition of the national vehicle fleet. LPG-powered vehicles also contributed to the overall rise in emissions. Their associated CO₂ output increased from 1.34 million tons in 2004 to 8.79 million tons in 2024, reflecting the growing popularity of LPG due to its relative affordability and tax advantages. In contrast, emissions from gasoline vehicles remained relatively stable. While gasoline-related emissions were around 9.38 million tons in 2004, they rose only modestly to 11.3 million tons by 2024. This modest growth includes a period of decline between 2004 and 2012, followed by a gradual increase in subsequent years, likely reflecting a mix of vehicle replacement trends, consumer preferences, and engine efficiency improvements. Overall, the trends presented in Figure 2 underscore that the increase in transportation-related carbon emissions in Turkey is largely attributable to the growing prevalence of fossil fuel-powered vehicles, especially diesel and LPG. These findings highlight the urgent need for a structural transition in the Turkish transportation sector toward lower-emission alternatives, reinforced by changes in fuel taxation, vehicle technology, and mobility policies.

2.3. Time series forecasting model

In this study, historical vehicle data for three primary fossil fuel types gasoline, diesel, and liquefied petroleum gas (LPG) were utilized. The dataset, obtained from national traffic and energy authorities, spans the period from 2004 to 2024 and includes the annual vehicle counts for each fuel type. The data were stored in a semicolon-separated CSV file (gasoline_lpg_diesel.csv) and were pre-processed using the pandas library (v1.5.3) in the Python programming environment (v3.11). To facilitate regression modelling, the Year column was converted to a numeric variable (Year_Num) and reshaped into a two-dimensional array suitable for scikit-learn models.

2.3.1. Forecasting Approach: Polynomial Regression

Polynomial regression is a statistical technique used to model non-linear relationships between variables. It has proven particularly effective in analysing and forecasting complex data structures. For instance, one study compared polynomial regression with artificial neural networks for predicting electricity consumption in lighting systems and found that while both methods achieved similar accuracy levels, polynomial regression offered a simpler and more interpretable model (Belany et al., 2024). Another study demonstrated the effectiveness of polynomial regression in engineering applications, especially for modelling stress conditions (Ostertagová, 2012). These studies highlight the practicality and reliability of polynomial regression in both engineering and energy-related domains.

A second-degree polynomial regression model was selected for each fuel type to capture non-linear trends in fuel-based vehicle adoption. Polynomial regression is more flexible in modelling real-world patterns than linear models, especially when saturation or declining trends are expected (e.g., for diesel vehicles). The performance of the polynomial regression models was evaluated using the coefficient of determination (R^2), which showed strong goodness-of-fit for all fuel types: 0.90 for gasoline, 0.98 for diesel, and 0.99 for LPG. These values indicate a high level of predictive accuracy and reliability of the models for future trend estimation.

For each fuel type $f \in \{Gasoline, Diesel, LPG\}$, the vehicle count V_f was modeled as a quadratic function of year t , as shown in (Eq.1):

$$V_{f(t)} = \beta_0 + \beta_1 t + \beta_2 t^2 + \varepsilon \quad (1)$$

Polynomial feature transformation was applied using the Polynomial Features function with a degree of 2 from the scikit-learn preprocessing module. This was followed by model fitting using the Linear Regression algorithm. Forecasts were produced for the years 2025 to 2040. To maintain realistic projections, negative prediction values were adjusted to zero, and excessively high values were limited to no more than three times the last observed value in 2024 for each fuel type. This method was chosen to ensure the stability of the model while preserving its interpretability.

2.3.2. Policy Scenario Design

Three future scenarios were defined to assess the impact of policy interventions and market evolution on fossil fuel vehicle usage. The first scenario, named the Advanced Sustainable Policy Scenario (ASPS), assumes strong incentives for electric vehicles along with a regulatory phase-out of diesel vehicles and a significant decline in gasoline and LPG vehicle adoption after 2035. The second scenario, called the Moderate Sustainable Policy Scenario (MSPS), envisions a gradual transition to electric vehicles supported by moderate policy incentives and a steady reduction in diesel vehicle usage. The third scenario, referred to as the Usual Fossil Fuel Scenario (UFFS), represents a baseline case with minimal policy intervention, in which internal combustion engine vehicles continue to dominate the market.

Each scenario includes decay factors $\alpha_f(t)$ for each fuel type, which are applied multiplicatively to the base forecasts as described in (Eq.2). This formulation allows the model to incorporate the effects of different policy interventions and market conditions on future vehicle fleet compositions:

$$V_{f,scenario}(t) = V_{f,base}(t) \cdot \alpha_f(t) \quad (2)$$

These decay functions were defined as piecewise linear reductions tailored to policy stringency, reflecting expected behavioural shifts and market transitions.

2.2.3. Visualization and Comparative Assessment

To evaluate the implications of each scenario, various visualization techniques were used. Scenario-specific fuel trajectory plots were generated to illustrate the projected vehicle counts for each fuel type under different policy scenarios. In addition, bar plots were created to compare the number of gasoline, diesel, and LPG vehicles in the target years of 2030, 2035, and 2040. Stacked bar charts were utilized to show the overall distribution of vehicle types across scenarios, highlighting changes in fuel mix. Furthermore, electric vehicle penetration rates were estimated heuristically based on the assumptions defined in each scenario, such as a linear increase reaching approximately 55% by 2040 in the Advanced Sustainable Policy Scenario. All visualizations were produced using the matplotlib library, with a uniform style setting (seaborn-whitegrid) and a consistent colour palette to enhance readability and visual coherence.

2.3. Carbon footprint calculation method

The carbon footprint was calculated using the projected number of vehicles and the emission factors specific to each fuel type. Hybrid and electric vehicles were excluded from this calculation because of limited historical data and their negligible direct CO₂ emissions. The estimation approach follows the Tier 1 methodology recommended by the Intergovernmental Panel on Climate Change (IPCC, 2006), in which total CO₂ emissions are derived from vehicle count, emission factors, and average annual mileage. The annual average mileage per vehicle was assumed to be 10,000 kilometers, also in accordance with IPCC (2006). Vehicle registration data categorized by fuel type were obtained from the Turkish Statistical Institute (TÜİK), and the mileage assumption was applied to standardize the calculations, facilitate future scenario modeling, and ensure comparability with international greenhouse gas inventories. The basic formula used is presented in Eq. 3:

$$\text{Total CO}_2 \text{ Emission (ton/year)} = \frac{\text{Number of vehicles} \times \text{Emission factor} \times \text{Average annual Km}}{1000} \quad (3)$$

Where:

- Number of Vehicles: The projected number of gasoline, diesel and LPG vehicles.
- Emission Factor: The carbon emission value in kg CO₂/km based on IPCC and TÜİK data.
- Average Annual Km: The assumed annual distance travelled per vehicle in Turkey.

2.3.1. Comparison of past and future carbon footprints

Carbon emissions for the years 2004-2024 were calculated and analysed. Carbon footprint projections for 2030, 2035, and 2040 were created based on predicted vehicle numbers. The impact of hybrid and electric vehicle adoption on reducing carbon emissions was evaluated.

3. Results

3.1. Factors influencing future vehicle trends

To better understand the dynamics shaping the transition from fossil-fuel-powered vehicles to sustainable mobility solutions in Turkey between 2030 and 2040, ten key factors have been identified. These factors encompass government policies, technological developments, energy sector transformations, demographic trends, and changes in consumer behaviour. National and international commitments, such as the Paris Agreement ratification, the 2053 Net Zero Emission Target, and the plan to phase out internal combustion engine vehicle sales by 2040, play pivotal roles in driving these transitions. Additionally, rapid advancements in battery technology, expansion of the electric vehicle

charging infrastructure, and the anticipated rise in environmental awareness among younger generations are expected to accelerate the adoption of electric and hybrid vehicles. The projected population growth and urbanization trends will further amplify transportation demand, creating an urgent need for sustainable mobility solutions. To explore how these key factors may influence future developments, three policy-driven scenarios have been constructed. These scenarios represent alternative pathways for Turkey's vehicle fleet composition and mobility transition, depending on the level and effectiveness of policy implementation. Each scenario outlines a different trajectory from ambitious decarbonization efforts to limited regulatory intervention highlighting potential implications for emissions, technology adoption, and fossil fuel dependency.

-Advanced sustainability policy scenario (ASPS)

This scenario represents a transformation pathway based on high-level policy intervention, where strong legal and economic instruments are implemented to accelerate sustainable mobility. The approach emphasizes a strategic shift away from fossil-fuel-powered vehicles, grounded in coordinated national and international efforts. According to this scenario, the European Union and Turkey are implementing strong sustainable transportation policies to achieve net-zero emissions by 2050, focusing on electric vehicle adoption and phasing out internal combustion engines (Dönmezçelik et al., 2023; Hart et al., 2024). Strategies include fuel taxes, penalties for polluting vehicles, and scrappage subsidies (Hart et al., 2024). Electrification is considered essential, with some projections indicating that up to 97% of the vehicle fleet could consist of plug-in hybrid or battery electric vehicles by 2050 (Hörtl et al., 2017). However, this shift may lead to increased electricity demand, necessitating complementary policies to prevent the transfer of emissions to other sectors. Tank-to-wheel CO₂ emission reductions of up to 90% compared to 1990 levels are deemed possible through strong fleet electrification and energy efficiency measures (Krause et al., 2020). Achieving these targets will require a combination of technological innovation, changes in mobility patterns, and prioritization of energy demand decarbonization (Dönmezçelik et al., 2023; Hörtl et al., 2017).

-Moderate sustainability policy scenario (MSPS)

This alternative represents a cautious and balanced transition approach, where sustainable mobility goals are pursued without overly aggressive measures. Policy trade-offs, sectoral priorities, and regional energy contexts are carefully weighed to avoid unintended consequences.

The transition to sustainable mobility presents complex challenges, with electric vehicles (EVs) playing a contentious role. While EVs are often seen as a sustainable solution, their environmental impact depends on electricity sources and manufacturing processes (Cremades & Canals Casals, 2022). Large-scale EV adoption may divert resources from other sustainable mobility measures like compact city development and public transport promotion (Driscoll et al., 2012). Balancing EV incentives with public transportation investment and fossil fuel taxation can help achieve sustainability goals, but excessive EV subsidies may increase pollution in countries relying on non-renewable energy (Asgarian et al., 2024). Current policies are insufficient to meet climate targets, and a rapid, large-scale reduction in car use is necessary alongside vehicle design improvements to comply with Paris Agreement carbon budgets (Winkler et al., 2023). The transition to sustainable mobility requires a comprehensive approach, considering various policy options and their long-term impacts on emissions and energy demand.

-Usual fossil fuel scenario (UFFS)

This scenario outlines a future where internal combustion engine (ICE) vehicles remain dominant due to weak policy interventions and limited progress in power sector decarbonization. The transport sector, responsible for 24% of global energy-related greenhouse gas emissions, faces challenges in transitioning to low-carbon alternatives (Fulton et al., 2013). While electric vehicles are often seen as a solution, their effectiveness depends on decarbonizing the power sector (Zhang et al., 2014). Internal combustion engines (ICEs) are projected to remain dominant until 2040, with potential for significant efficiency improvements and reduced environmental impact (Leach et al., 2020). A comprehensive approach

combining lifestyle changes, socio-cultural factors, and technological advancements is crucial for achieving substantial emissions reductions (Brand et al., 2019). Integrating transport electrification with sustainable socioeconomic pathways can lead to a low-carbon transition and potentially reduce mitigation costs (Zhang et al., 2014). However, meeting legislated carbon budgets may require a combination of radical changes in travel patterns, vehicle choice, and behaviour alongside high electrification and phasing out of conventional vehicles (Brand et al., 2019). These three scenarios provide distinct projections for the evolution of vehicle fuel type distributions in Turkey between 2030 and 2040. The quantitative implications of each scenario are summarized in Table 3. A graphical representation of these projections is provided in Figure 3.

Table 3. Projected Fuel Type Distribution in Turkey Under Alternative Policy Scenarios (2030–2040)

Year	Scenario	Gasoline	Diesel	LPG
2030	Advanced Sustainable Policy Scenario	5930350	5766202	4229159
2030	Moderate Sustainable Policy Scenario	6628038	6535029	4464112
2030	Usual Fossil Fuel Scenario	6802460	7303856	4581589
2035	Advanced Sustainable Policy Scenario	6913753	4556654	3025731
2035	Moderate Sustainable Policy Scenario	8889111	6379315	3403947
2035	Usual Fossil Fuel Scenario	9382951	8201977	3593056
2040	Advanced Sustainable Policy Scenario	6096358	1051361	1510239
2040	Moderate Sustainable Policy Scenario	10837970	5256807	1858756
2040	Usual Fossil Fuel Scenario	12531403	8936573	2149187

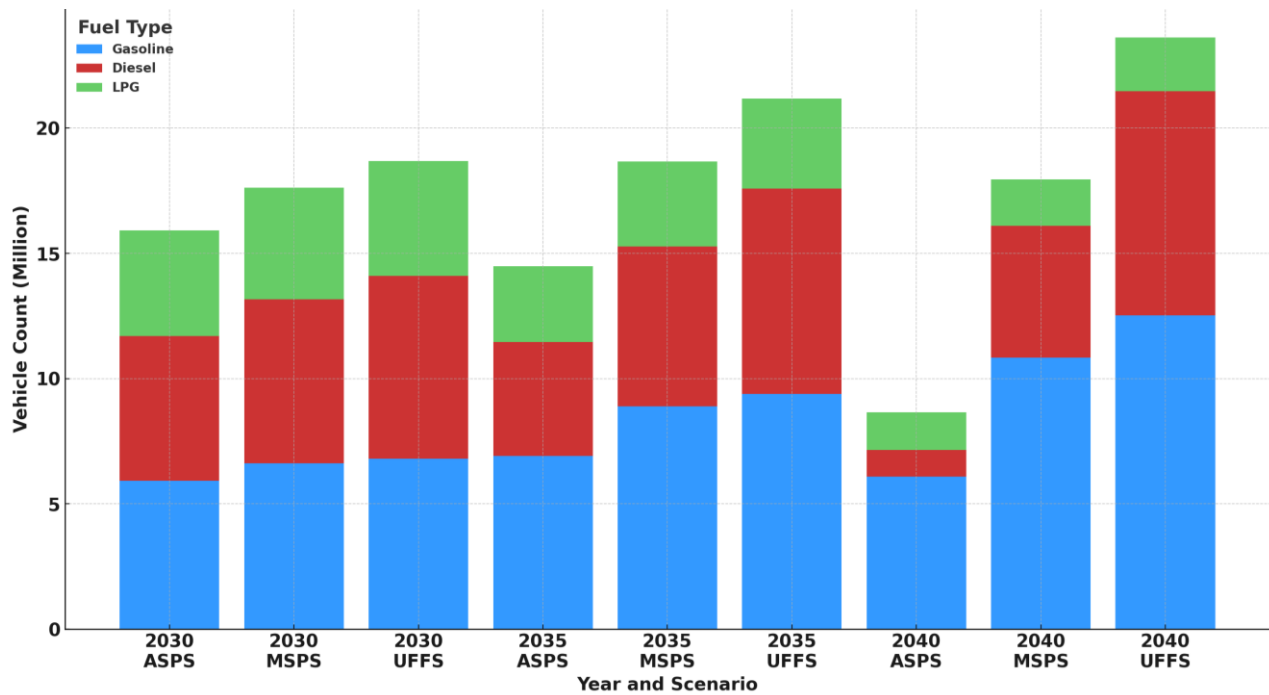


Figure 3. Scenario based forecasts by fuel types

In order to assess the implications of different policy interventions, Figure 4 presents the projected CO₂ emissions from Turkey's road transport sector between 2030 and 2040 under three distinct scenario.

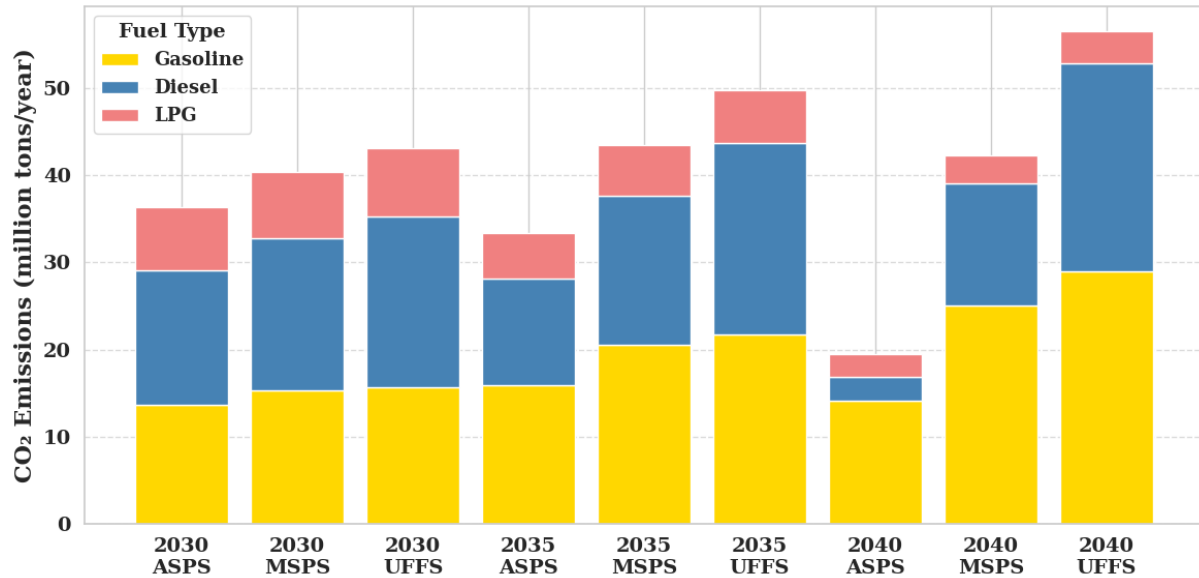


Figure 4. Projected carbon footprint by fuel and scenario (2030-2040)

The updated Figure 2 clearly demonstrates a substantial increase in CO₂ emissions from Turkey's transportation sector between 2004 and 2024. While total emissions were approximately 11.5 million tons of CO₂ in 2004, they exceeded 27 million tons by 2024. This increase is predominantly driven by the rapid expansion of diesel-powered vehicles. Diesel-related emissions rose from just 677,000 tons in 2004 to 14.85 million tons in 2024, representing a more than twentyfold increase. Emissions from gasoline vehicles remained relatively stable, increasing from 9.38 million tons to 11.33 million tons over the same period. Meanwhile, LPG-related emissions showed a more balanced rise, growing from 1.34 million tons in 2004 to 8.79 million tons in 2024. These figures reflect the growing share of diesel and LPG vehicles in the fleet and emphasize the inadequacy of low-intervention policy environments in curbing emission growth. Figure 4, which presents emission projections for 2030, 2035, and 2040 under three different policy scenarios the Advanced Sustainability Policy Scenario (ASPS), Moderate Sustainability Policy Scenario (MSPS), and Usual Fossil-Fuel Scenario (UFFS) illustrates the potential outcomes of differing policy intensities. Under the ASPS, the transportation sector undergoes a significant transformation, with a sharp decline in both diesel and LPG usage. By 2040, total emissions are reduced to approximately 19.1 million tons of CO₂, indicating a more than 30% decrease compared to 2024 levels. Particularly notable is the reduction in diesel-related emissions, which fall from over 14 million tons to just above 8 million tons, illustrating the effectiveness of ambitious and comprehensive policy action. In contrast, the MSPS scenario represents a partially transformed system in which electrification begins but fossil-fuel vehicles especially gasoline-powered ones still dominate. Under this pathway, total emissions in 2040 rise to over 25 million tons of CO₂, surpassing the 2024 level. Gasoline-related emissions alone exceed 25 million tons, highlighting the limited effectiveness of moderate intervention in reducing emissions meaningfully. The UFFS scenario, which assumes a continuation of existing trends without significant policy changes, projects emissions rising to more than 32 million tons of CO₂ by 2040. Diesel emissions climb to nearly 24 million tons, gasoline emissions exceed 28 million tons, and LPG-related emissions reach 3.6 million tons, reinforcing the unsustainability of a business-as-usual trajectory. Together, Figures 2 and 4 underscore the critical importance of policy ambition and coordination in shaping the future carbon footprint of Turkey's transportation sector. Without decisive measures such as accelerated vehicle electrification, the phasing out of diesel vehicles, structural fiscal disincentives for fossil fuel use, and substantial investments in charging infrastructure emissions are likely to continue rising. This trajectory would place Turkey's 2053

Net Zero Emission Target at significant risk. The ASPS scenario provides a realistic and necessary roadmap to reverse the historical upward trend and align the sector with national and global climate commitments.

4. Conclusions

This study analysed the historical evolution of vehicle technologies in Turkey between 2004 and 2024 and projected their future distribution and environmental impact for 2030, 2035, and 2040 using polynomial regression-based time series models. The findings demonstrate that the widespread adoption of electric and hybrid vehicles is crucial for achieving sustainable transport goals. Without strong policy interventions, carbon emissions from the transport sector are expected to continue rising significantly.

Key findings:

- Sharp increase in diesel and LPG vehicles: Transport-related carbon dioxide (CO₂) emissions rose from 11.5 million tons in 2004 to over 27 million tons in 2024, primarily due to the rapid expansion of diesel and LPG vehicles. Diesel-related emissions alone surged from 0.68 million tons to 14.9 million tons.
- Post-2010 diesel boom: The widespread adoption of diesel vehicles after 2010 drove total sectoral emissions to more than double their 2004 level by 2024.
- Advanced Sustainability Policy Scenario (ASPS): Phasing out fossil-fuel-powered vehicles and accelerating the uptake of electric vehicles could reduce emissions to approximately 19 million tons of CO₂ by 2040—more than a 30% reduction compared to 2024 levels.
- Moderate Sustainability Policy Scenario (MSPS): Partial electrification results in only limited emission reduction, with total emissions stabilizing around 25 million tons of CO₂ by 2040.
- Usual Fossil-Fuel Scenario (UFFS): If current trends continue, emissions are projected to exceed 32 million tons of CO₂ by 2040, reinforcing the historical growth trajectory.

Recommendations:

- Accelerate e-mobility transition: Promote the adoption of battery-electric and hybrid vehicles through purchase incentives, tax exemptions, and extensive charging infrastructure.
- Gradual phase-out of fossil-fuel vehicles: Implement progressive taxation and regulatory limits on new diesel and gasoline vehicles, alongside just-transition measures for impacted sectors.
- Integrated decarbonisation of power and transport sectors: The benefits of electrification depend on a parallel transition to a low-carbon electricity grid; otherwise, upstream emissions may undermine end-use gains.
- Data-driven governance: Continuous, high-resolution data from TÜİK, EPDK, and the Ministry of Environment should support dynamic, evidence-based policy adjustments in collaboration with academic modelling.
- Public engagement: National awareness campaigns and educational initiatives are vital to foster behavioural change and public acceptance of low-carbon mobility solutions.
- By combining robust time series forecasting with detailed carbon footprint modelling, this study provides an actionable roadmap for aligning Turkey's transport sector with its 2053 Net Zero Emission Target and contributes to the global discourse on sustainable mobility transitions.

Researchers' Contribution Rate Statement

The first version of the study was prepared by the corresponding author and the second author and edited and reviewed.

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References

- Ağbulut, Ü.** (2022). Forecasting of transportation-related energy demand and CO2 emissions in Turkey with different machine learning algorithms. *Sustainable Production and Consumption*, 29, 141-157. <https://doi.org/10.1016/j.spc.2021.10.001>
- Asgarian, F., Hejazi, S. R., Khosroshahi, H., & Safarzadeh, S.** (2024). Vehicle pricing considering EVs promotion and public transportation investment under governmental policies on sustainable transportation development: The case of Norway. *Transport Policy*, 153, 204-221. <https://doi.org/10.1016/j.tranpol.2024.05.017>
- Awan, A., Alnour, M., Jahanger, A., & Onwe, J. C.** (2022). Do technological innovation and urbanization mitigate carbon dioxide emissions from the transport sector? *Technology in Society*, 71, 102128. <https://doi.org/10.1016/j.techsoc.2022.102128>
- Belany, P., Hrabovsky, P., Sedivy, S., Cajova Kantova, N., & Florkova, Z.** (2024). A Comparative Analysis of Polynomial Regression and Artificial Neural Networks for Prediction of Lighting Consumption. *Buildings*, 14(6), 1712. <https://doi.org/10.3390/buildings14061712>
- Bleviss, D. L.** (2021). Transportation is critical to reducing greenhouse gas emissions in the United States. *WIREs Energy and Environment*, 10(2), e390. <https://doi.org/10.1002/wene.390>
- Brand, C., Anable, J., & Morton, C.** (2019). Lifestyle, efficiency and limits: Modelling transport energy and emissions using a socio-technical approach. *Energy Efficiency*, 12(1), 187-207. <https://doi.org/10.1007/s12053-018-9678-9>
- Cevheribucak, G.** (2021). Energy Transition and Sustainable Road Transportation in Turkey: Multiple Policy Challenges for Inclusive Change. *Frontiers in Sustainable Cities*, 3, 631337. <https://doi.org/10.3389/frsc.2021.631337>
- Cremades, L., & Canals Casals, L.** (2022). Analysis of the Future of Mobility: The Battery Electric Vehicle Seems Just a Transitory Alternative. *Energies*, 15(23), 9149. <https://doi.org/10.3390/en15239149>
- Dalianis, G., Nanaki, E., Xydis, G., & Zervas, E.** (2016). New Aspects to Greenhouse Gas Mitigation Policies for Low Carbon Cities. *Energies*, 9(3), 128. <https://doi.org/10.3390/en9030128>
- De Abreu, V. H. S., Santos, A. S., & Monteiro, T. G. M.** (2022). Climate Change Impacts on the Road Transport Infrastructure: A Systematic Review on Adaptation Measures. *Sustainability*, 14(14), 8864. <https://doi.org/10.3390/su14148864>
- Dönmezçelik, O., Koçak, E., & Örkücü, H. H.** (2023). Towards net zero emissions target: Energy modelling of the transport sector in Türkiye. *Energy*, 279, 128064. <https://doi.org/10.1016/j.energy.2023.128064>
- Driscoll, P. A., Theodórsdóttir, Á. H., Richardson, T., & Mguni, P.** (2012). Is the Future of Mobility Electric? Learning from Contested Storylines of Sustainable Mobility in Iceland. *European Planning Studies*, 20(4), 627-639. <https://doi.org/10.1080/09654313.2012.665036>
- Ferrer, A. L. C., & Thomé, A. M. T.** (2023). Carbon Emissions in Transportation: A Synthesis Framework. *Sustainability*, 15(11), 8475. <https://doi.org/10.3390/su15118475>

- Fulton, L., Lah, O., & Cuenot, F.** (2013). Transport Pathways for Light Duty Vehicles: Towards a 2° Scenario. *Sustainability*, 5(5), 1863-1874. <https://doi.org/10.3390/su5051863>
- Güzel, T. D., & Alp, K.** (2020). Modeling of greenhouse gas emissions from the transportation sector in Istanbul by 2050. *Atmospheric Pollution Research*, 11(12), 2190-2201. <https://doi.org/10.1016/j.apr.2020.08.034>
- Hart, R., Kyriakopoulou, E., & Lu, T.** (2024). Urban Transport Policies and Net Zero Emissions in the European Union. *Annual Review of Resource Economics*, 16(1), 187-206. <https://doi.org/10.1146/annurev-resource-101623-101611>
- Hörtl, A., Macharis, C., & De Brucker, K.** (2017). Pathways to Decarbonise the European Car Fleet: A Scenario Analysis Using the Backcasting Approach. *Energies*, 11(1), 20. <https://doi.org/10.3390/en11010020>
- IPCC.** (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy. Intergovernmental Panel on Climate Change. Erişim Tarihi, 20 Haziran 2025, <https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html>
- Isik, M., Sarica, K., & Ari, I.** (2020). Driving forces of Turkey's transportation sector CO2 emissions: An LMDI approach. *Transport Policy*, 97, 210-219. <https://doi.org/10.1016/j.tranpol.2020.07.006>
- Katircioğlu, S., & Katircioğlu, S.** (2018). Testing the role of urban development in the conventional Environmental Kuznets Curve: Evidence from Turkey. *Applied Economics Letters*, 25(11), 741-746. <https://doi.org/10.1080/13504851.2017.1361004>
- Krause, J., Thiel, C., Tsokolis, D., Samaras, Z., Rota, C., Ward, A., Prenninger, P., Coosemans, T., Neugebauer, S., & Verhoeve, W.** (2020). EU road vehicle energy consumption and CO2 emissions by 2050 – Expert-based scenarios. *Energy Policy*, 138, 111224. <https://doi.org/10.1016/j.enpol.2019.111224>
- Leach, F., Kalghatgi, G., Stone, R., & Miles, P.** (2020). The scope for improving the efficiency and environmental impact of internal combustion engines. *Transportation Engineering*, 1, 100005. <https://doi.org/10.1016/j.treng.2020.100005>
- Linton, C., Grant-Muller, S., & Gale, W. F.** (2015). Approaches and Techniques for Modelling CO2 Emissions from Road Transport. *Transport Reviews*, 35(4), 533-553. <https://doi.org/10.1080/01441647.2015.1030004>
- Naimoglu, M., & Akal, M.** (2023). The relationship between energy technology, energy efficiency, renewable energy, and the environment in Türkiye. *Journal of Cleaner Production*, 418, 138144. <https://doi.org/10.1016/j.jclepro.2023.138144>
- Ostertagová, E.** (2012). Modelling using Polynomial Regression. *Procedia Engineering*, 48, 500-506. <https://doi.org/10.1016/j.proeng.2012.09.545>
- Springel, K.** (2021). It's Not Easy Being "Green": Lessons from Norway's Experience with Incentives for Electric Vehicle Infrastructure. *Review of Environmental Economics and Policy*, 15(2), 352-359. <https://doi.org/10.1086/715549>
- Stamos, I., Mitsakis, E., & Grau, J. M. S.** (2015). Roadmaps for Adaptation Measures of Transportation to Climate Change. *Transportation Research Record: Journal of the Transportation Research Board*, 2532(1), 1-12. <https://doi.org/10.3141/2532-01>
- Şen, M., Yiğiter, M. S., & Özcan, M.** (2023). Why are consumers switching to electric vehicles? Analyzing consumers preferences for electric vehicles. *Case Studies on Transport Policy*, 14, 101108. <https://doi.org/10.1016/j.cstp.2023.101108>
- TÜİK.** (2025.). TÜİK veri portalı, Erişim tarihi 25 Şubat 2025, <https://data.tuik.gov.tr/Kategori/GetKategori?p=ulasirma-ve-haberlesme-112&dil=1>
- Winkler, L., Pearce, D., Nelson, J., & Babacan, O.** (2023). The effect of sustainable mobility transition policies on cumulative urban transport emissions and energy demand. *Nature Communications*, 14(1), 2357. <https://doi.org/10.1038/s41467-023-37728-x>
- Zhang, X., Xie, J., Rao, R., & Liang, Y.** (2014). Policy Incentives for the Adoption of Electric Vehicles across Countries. *Sustainability*, 6(11), 8056-8078. <https://doi.org/10.3390/su6118056>