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Analysis of Passenger Car Tailpipe Emissions in Different World Regions through 2050

Murat Senzeybek *, Mario Feinauer, Isheeka Dasgupta and Simone Ehrenberger

Institute of Vehicle Concepts, German Aerospace Center (DLR), Pfaffenwaldring 38–40, 70569 Stuttgart, Germany; isheeka.dasgupta@dlr.de (I.D.); simone.ehrenberger@dlr.de (S.E.)
* Correspondence: murat.senzeybek@dlr.de

Abstract: This study presents a carbon dioxide (CO_2), exhaust particulate matter ($PM_{2.5}$) and nitrogen oxide (NO_x) tailpipe emission analysis of passenger cars in nine countries, representing different world regions up to 2050 using a bottom-up calculation method. A diffusion model is used to analyze the development of different drivetrain/fuel technologies in the respective vehicle stocks of each world region. Drivetrain- and country-specific emission factors are weighted according to the modelled stock compositions. The obtained stock fleets' average emission factors are multiplied by the transport demand in order to obtain the total passenger car emissions. Our findings reveal global passenger car CO_2, NO_x and $PM_{2.5}$ emissions decrease by approximately 45%, 63% and 54%, respectively, between 2015 and 2050. Gasoline will remain a significant energy carrier in 2050 with about a 25% stock share. However, electric vehicles will be in the lead, especially after 2040. Additionally, rising transport demand offsets emission reductions in some regions. This study aims to provide global and regional insights into future emissions trends and their driving factors.

Keywords: passenger car fleets; global emission modelling; electrification; CO_2 emissions; NO_x emissions; PM emissions

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1. Introduction

Anthropogenic greenhouse gas (GHG) and pollutant emissions need to be reduced in order to combat climate change and further environmental issues like air quality in urban areas. Transportation is of particular interest as it is one of the major emission-causing sectors. According to the International Energy Agency [1], in 2019, transportation accounted for 15% of global GHG emissions. Road transport is largely responsible for this, accounting for two-thirds of transport-related CO_2-eq emissions. Consequently, passenger cars take on a significant role as they constitute the majority share of road transportation. In addition to CO_2, the emissions of NO_x and $PM_{2.5}$ are particularly harmful to human health, which emphasizes the critical importance of addressing these pollutants in environmental impact assessments.

In order to analyze energy use, land use and emissions of relevant sectors and their impacts on climate change, the Shared Socioeconomic Pathways (SSPs) scenario framework has been established. The SSPs describe plausible and internally consistent views of society's future in terms of demographic, economic, technological, social, political and environmental factors in five narratives which encompass various challenges of climate change mitigation and adaption [2]: SSP1—Sustainability, SSP2—Middle of the Road, SSP3—Regional Rivalry, SSP4—Inequality and SSP5—Fossil-fueled Development. Riahi et al. [3] provide a detailed and comprehensive overview of the SSPs. Based on these pathways, several large scenario studies have been conducted for the IPCC Assessment Reports. In this context, Integrated Assessment Models (IAMs) are used to comprehensively assess global energy, economic, land, climate and environmental systems [4]. For work with IAMs, the SSP scenarios are coupled with climate targets via Representative Concentration Pathways (RCPs) to provide a unified framework for socioeconomic developments and the level of GHG emissions to be achieved. They support modelers to improve the comparability of results and to account for uncertain state-of-knowledge developments, such as population growth, food preferences, environmental awareness or international cooperation [5].

IAMs can map a wide range of possible future scenarios and their linkages to technical and socioeconomic developments and policy decisions. However, they barely enable a differentiated analysis of specific subsectors, modes, markets, countries or technologies. For instance, according to van Vuuren et al. [6], global passenger car travel demand will significantly increase from 2010 to 2050, especially within the SSP2 scenario. But the impacts of increasing activity levels on passenger car energy demands and emissions vary depending on the degree and pace of the circulation of electrified drivetrain technologies, which enable high energy efficiencies and reduced or zero tailpipe emissions. The technological development of passenger car fleets, in turn, varies depending on vehicle market mechanisms and political targets in the various countries or regions. Also, the boundary conditions on the passenger car markets have significantly changed in recent years, for instance, due to advanced battery technology, increased fossil fuel costs and government plans or regulations on phasing out fossil fuel vehicles globally. However, the IPCC report lacks clear differentiation among the greenhouse gas emissions attributed to different modes of transportation, and there is a gap in the literature regarding the total CO_2, NO_x and $PM_{2.5}$ emissions that are only from passenger cars. This study was part of a work which intended to provide the individual contributions of additional pollutant species like black carbon, CH_4, CO, HC, NH_3, NO_2, SO_2, etc., apart from CO_2, NO_x and $PM_{2.5}$ as an input to transport emission inventories. This is intended so as to not just look at emissions from a greenhouse gas perspective but also as an input to air quality and climate change models in which in each species has independent interactions that contribute to direct and indirect greenhouse and aerosol effects. To capture the mesoscale and regional effects of air pollution, it is important to estimate emissions globally for each sector and subsector, like the emissions of passenger cars and trucks, which are governed by separate policies.

Given these reasons, this study aims at modelling global passenger car emissions between 2015 and 2050 from the bottom up in a country-differentiated manner. The selected countries we focused on are Australia, Brazil, China, Germany, India, Japan, Russia, South Africa and the USA. This country selection includes both countries that cover a relevant geographic area globally and also the main vehicle markets that have a leading role in establishing new technology trends, e.g., the electrification of drivetrains. In addition to being the largest passenger car markets in their respective regions, these nine countries collectively account for 58% of the global passenger car stock [7]. Hereby, we analyze relevant drivetrain technologies and their development in these countries' vehicle stock fleets. This is based on diffusion modelling, which considers current policy electrification targets to analyze the market entry and development of different drivetrain/fuel technologies in the respective vehicle stocks of each country. Further, drivetrain- and country-specific emission factors are derived and subsequently aggregated according to the modelled stock fleet compositions. The obtained stock fleets' average emission factors are multiplied with the transport demand in order to obtain the total passenger car emissions. For the emissions calculation of the other countries of the world, a cluster approach is considered. Thereby, all countries globally are assigned to one of nine world regions. It is assumed that each country within one world region has the same stock fleet average emission factor, based on the respective focus country analysis. The allocation of countries to world regions is described in Appendix C. Apart from CO_2, NO_x and $PM_{2.5}$ are considered, as these pollutant emissions can be relevant not only regarding air quality impact assessments but also for climate modelers in terms of indirect climate effects.

This paper is organized as follows. Firstly, in the Materials and Methods section (Section 2), our bottom-up approach is explained comprehensively (Section 2.1), followed by several sections for the individual inputs going into it, i.e., drivetrain technology market modelling (Section 2.1.1), research on emission factors (Sections 2.1.2 and 2.1.3) and the transport demand data considered herein (Section 2.1.4). Next, the results are presented in four sections: the differentiated passenger car market modelling results (Section 3.1), an overview of the global emissions development per world region (Section 3.2) and the CO_2 and pollutant emission analyses per country (Sections 3.3 and 3.4). Sections 4 and 5 follow with a discussion of the results and our conclusions.

2. Materials and Methods

2.1. Bottom-Up Emission Calculation Procedure

The annual passenger car emissions for each country were calculated in a bottom-up manner at the country level using country-specific activity data, which are the transport demand in vehicle kilometers for cars for the specified year and the associated stock-fleet-average emission factors for the country in that year.

$$E_{t,c,x} = T_{t,c} * EF_{x,t} \quad (1)$$

$$EF_{x,t} = \sum_{f} m_{t,f} * ef_{x,\, f,t} \quad (2)$$

where E is the passenger car emissions for pollutant species x in year t in country c which had a composition of f passenger car drivetrains with market share of m stock fleet shares at that time. This is obtained from the transport demand $T_{t,c}$, which is the vehicle km and the fleet average emission factor $EF_{x,t}$ in grams per km driven. The fleet-average emission factor is the emission factors ef in the year t for a given pollutant species and drivetrain (drivetrain-specific emission factors) weighted by the market share m of the stock of drivetrain f in the country.

2.1.1. Market Development of Drivetrain Technologies

In 2021, the electric vehicle market share in new passenger car registration exceeded 15% in Germany and China, two of the world's biggest automotive markets, according to Marklines [8]. However, the crucial factor for reducing passenger car emissions is the proportion of these vehicles in the overall vehicle stock. Even though electric vehicles (EVs) have gained widespread attention, their share in the global passenger car fleet remains at only approximately 1.4% [9], with a significant concentration of EVs in China, the USA and EU countries. To achieve a significant reduction in global emissions, it is crucial to extend the EV transformation beyond a few countries and expand it worldwide. As discussed in Section 2.1.4, transportation demand is expected to increase in some developing countries, such as India and Brazil, while it will be nearly constant in European countries. However, the number of electric cars in stock, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), is negligible at the moment in those countries, as can be seen in Figure 1.

In order to effectively assess the emissions of vehicles in the stock, it is crucial to analyze the powertrain distribution of the vehicles in question. Although many different sources are available for the diffusion of alternative powertrains, it is difficult to find a centralized analysis that covers many different regions individually and is updated frequently to cover new industry development, such as the EU internal combustion engine (ICE) ban [10]. Therefore, for this study, we used our function to be able to cover the recent developments in the industry.

The literature generally suggests that the market penetration of electric vehicles will follow an S-shaped curve, leading to numerous studies that utilize this method to analyze the market development of electric vehicles [11–13]. When data are available, S-shaped logistic growth functions are applicable to models of various scales and complexities, ranging from elementary particles to the evolution of stars because of their fractal characteristics [14]. As a result, the S-curve logistic growth function has been utilized in previous studies to analyze the growth of alternative powertrain shares across various regions globally [13,15]. The function used to estimate the stock share development of alternative powertrains is presented in Equation (3). $S_{c,p,t}$ is the share of powertrain p in country c at time t. $S0_{c,p}$ is the share of related powertrain at the time of zero (2015 in our model). $\Delta_{c,p}$ is the target share of the powertrain in country c. γ_c is the growth rate parameter of the country c based on the target year, and A is a scaling parameter that determines the initial growth rate of the market of the curve. More details about the functions are given in Appendix A.

$$S_{c,p,t}(unnormed) = S0_{c,p} + \frac{\Delta_{c,p}}{1 + A.e^{\gamma_c.(t-t_0)}} \quad (3)$$

$$S_{c,p,t} = \frac{S_{c,p,t}(unnormed)}{\sum_p S_{c,p,t}\,(unnormed)}$$

Equation (3) is a straightforward approach to estimate the future market shares of various powertrains in different countries. By comparing our results with existing studies and literature in Section 3.1, we ensure that our calculations are in parallel with our expectations based on reputable sources. The main input in the current model is the target shares. Those target shares in the model are based on the announced targets from the government of selected countries or analyses from different studies. Table 1 shows the target shares used in the model and the sources those shares are based on.

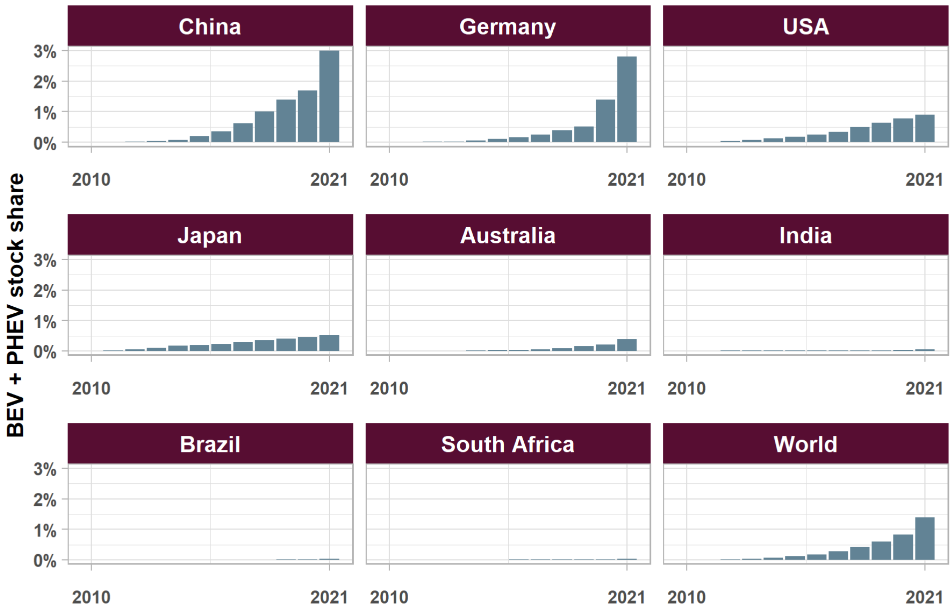


Figure 1. Electric car (BEV + PHEV) stock share of selected countries. Source: [9].

Table 1. Electrification targets used in the model and the sources the values are based on.

Region/ Country	Target Stock BEV Share	Target Year	Literature Considered	Source
Australia	70%	2065	65% sales in 2050	[16]
			Total BEV and PHEV sales share will be 30% in 2030	[17]
OECD Europe (Germany)	100%	2060	100% BEV new registrations in 2035	[10]
North America (the USA)	100%	2060	100% government vehicles in 2035	[18]
			50% electric vehicle sales share in 2030	[19]
			10 US states are in the ZEV Alliance, which is aiming for 100% EV sales between 2035 and 2050.	[20]
China	100%	2060	Net 0 in 2060	[21]

Table 1. *Cont.*

Region/Country	Target Stock BEV Share	Target Year	Literature Considered	Source
India	75%	2070	30% sales in 2030 and 75% in 2050	[22]
			15–20% sales in 2030	[23]
			EV stock in 2040 is 10% in Stated Policies Scenario and 60% in Sustainable Development Scenario	[24]
Japan	60%	2050	100% HEV or EV sales in 2030	[25]
Africa (South Africa)	65%	2070	40% of fleet will be EV by 2050	[26]
			50% stock share in 2050	[27]
			80% new sales will be EVs in 2045	[28]
South America (Brazil)	15%	2050	61% hybrid and 11% BEV fleet in 2050	[29]
Eastern Europe (Russia)	10%	2055	10% sales in 2030	[30]

2.1.2. CO_2 Emission Factors

Tailpipe CO_2 emission factors are computed based on the transport scenario model TRAEM (Transport Energy Model), which provides passenger car energy intensity figures from 2015 to 2050 differentiated by drivetrain technology and world region, assuming that energy efficiency improves over time. The energy intensity data were derived from the German Aerospace Centre (DLR) vehicle databases and the state-of-the-art literature [15]. According to the considered country clustering, it is assumed that within each world region, all countries have the same CO_2 emission factors (cf. Appendix C). For each country, the emission factors per drivetrain technology are then weighted according to the vehicle stock shares of each drivetrain technology (cf. Section 3.1), which results in stock fleet average CO_2 emission factors.

Following this, Equation (4) is derived based on [31] to calculate the specific CO_2 emission factors as follows:

$$ef_{CO_2,d,f,t} = ec_{d,f,t} * (1-b) * r * \frac{1}{LHV_f} * \frac{\rho_f}{c_f} * \frac{1}{0.273} \quad (4)$$

where $ef_{CO_2,d,t}$ is the drivetrain (d), fuel (f) and time (t)-specific CO_2 emission factor in g/km, calculated based on fuel consumption. This can be obtained from the drivetrain and fuel-specific energy consumption per year ($ec_{d,f,t}$) in MJ/100 km, from which a biofuel rate b is subtracted in order to only regard the fossil fuel share. An on-road fuel economy gap factor r which varies between 1.2 and 1.7 is further applied to consider real-world energy consumption, and the term is then divided by the lower heating value of the respective fuel (LHV_f) in MJ/l for petrol and diesel and in MJ/m^3 for CNG. Further, the density of the fuel ρ_f in kg/L for petrol and diesel and in kg/m^3 for CNG along with a fuel dependent factor c_f are required. According to [31], c_f is 0.118 for petrol-fueled vehicles, 0.116 for diesel vehicles and 0.1336 for CNG vehicles. The applied biofuel rate values in Equation (4) are also based on TRAEM data for the reference scenario [15] and can be found in Table A1 in Appendix B.

The resulting region- and drivetrain-specific CO_2 emission factors for the base years 2015, 2030 and 2050 are presented in Table 2.

Table 2. Region- and drivetrain-specific CO_2 emission factors in 2015, 2030 and 2050.

Region/Country	Year	CO_2 EF (g/km)						
		G	**G-HEV**	**D**	**D-HEV**	**CNG**	**G-PHEV**	**D-PHEV**
Australia	2015	174.7	121.9	190.0	138.2	178.9	109.3	123.9
	2030	127.9	96.2	136.5	109.8	132.8	86.0	98.2
	2050	96.1	65.0	110.5	76.4	90.3	62.5	73.4
South America (Brazil)	2015	177.7	106.8	179.9	136.7	192.4	96.2	123.2
	2030	142.0	93.6	154.7	119.9	167.9	84.6	108.3
	2050	120.1	81.5	134.5	104.7	135.0	75.0	96.3
China	2015	138.2	116.4	162.6	119.2	182.1	125.9	-
	2030	109.0	76.5	114.1	80.8	135.3	106.4	-
	2050	82.7	55.5	89.5	59.6	90.8	83.9	-
OECD Europe (Germany)	2015	147.6	94.8	141.8	96.9	152.8	116.1	118.8
	2030	136.7	89.4	125.9	94.1	139.4	94.3	99.3
	2050	117.8	69.0	113.5	73.1	107.1	73.3	77.6
India	2015	223.8	113.7	203.9	143.6	184.5	147.8	186.5
	2030	150.3	95.4	174.7	135.5	155.6	117.6	167.0
	2050	112.8	77.6	133.0	121.9	117.0	94.9	149.1
Japan	2015	174.7	121.9	190.0	138.2	178.9	109.3	123.9
	2030	127.9	96.2	136.5	109.8	132.8	86.0	98.2
	2050	96.1	65.0	110.5	76.4	90.3	62.5	73.4
Eastern Europe (Russia)	2015	176.1	121.0	166.4	130.2	160.3	113.0	121.7
	2030	149.3	99.1	142.4	109.1	136.7	99.3	109.3
	2050	117.7	80.4	123.8	90.6	109.8	84.3	95.1
Africa (South Africa)	2015	200.9	133.1	196.8	141.4	196.9	144.5	138.6
	2030	164.3	114.0	152.9	122.4	196.9	116.5	111.5
	2050	130.8	91.7	132.1	100.6	197.0	99.0	94.4
North America (the USA)	2015	268.1	144.0	-	-	172.0	102.7	-
	2030	165.9	99.5	-	-	128.5	79.6	-
	2050	94.3	52.9	-	-	40.7	52.4	-

G: Gasoline, G-HEV: Gasoline hybrid electric vehicle, D: Diesel, D-HEV: Diesel hybrid electric vehicle, CNG: Compressed natural gas, G-PHEV: Gasoline plug-in hybrid electric vehicle, D-PHEV: Diesel plug-in hybrid electric vehicle.

2.1.3. Pollutant Emission Factors

Nine selected countries are analyzed in detail to obtain passenger car drivetrain-specific emission factors for two pollutant species, exhaust $PM_{2.5}$ and NO_x. It is assumed that each of the countries represent a respective world region. For each country, the emission factors for each drivetrain technology are then weighted according to the vehicle stock shares of each drivetrain technology (cf. Section 3.1), which results in stock fleet average emission factors. Each of the representative countries' fleet average emission factors are allocated to the remaining countries of the associated world region according to the country clusters described in Appendix C. Different approaches and data sources are considered for estimating the drivetrain-specific emission factors of each analyzed country. Table 3 summarizes the studied countries and the methods and references for the derivation of the pollutant emission factors.

Generally, the pollutant emission factors of gasoline and diesel hybrid electric vehicles (G-HEV and D-HEV) are set to be equal to the conventional gasoline- and diesel-fueled vehicles for each country. Plug-in hybrid electric vehicles' (PHEV) emission factors are estimated according to the Germany-based emission factor ratio between conventional gasoline/diesel vehicles and corresponding gasoline/diesel PHEVs. Therefore, PHEV emission factors for ICE driving are derived based on the emission factor development of conventional vehicles in each country. Given that PHEVs are less common in the small vehicle segment, their average ICE driving emissions tend to be higher. We used WLTP utility factors for PHEVs based on the curves from Eder et al. [32] for global applicability across different regions. It is also important to note that this study considers only exhaust $PM_{2.5}$ emissions, which account for only 20–40% of total $PM_{2.5}$ today, with the remaining stemming from traffic, including tire wear, brake wear and resuspension of dust. There exists high level of uncertainty in quantifying and measuring non-exhaust PM emissions with Euro 7 standards as the first to propose limits and testing criteria. With higher weight of PHEVs and EVs due to battery weight, non-exhaust sources of $PM_{2.5}$ would account for an even higher share. Thus there need to be more standardized emission factor studies globally to quantify emissions uniformly, which can then be used in transport emission inventories [33,34]. Compressed natural gas (CNG)-fueled vehicles' pollutant emission factors are based on the data sources for Germany, except India, for which country-specific data are considered.

Table 3. Overview of the pollutant emission factor estimation methods for the studied countries.

Region/ Country	Pollutant EF Estimation Method/Model	Source
Australia	EF weighting according to Euro class fleet shares; Estimation of the composition of the vehicle fleet by Euro class based on the time lag of the introduction of the Euro classes corresponding to Australian standards compared to that of Europe.	[35]
South America (Brazil)	Based on the São Paulo official vehicular emissions inventory (CETESB) and the stock distribution of vehicles by age of use (VEIN model).	[36,37]
China	Emission factors for gasoline vehicles (which constitute approximately 90% of the stock fleet in 2015) until 2030 based on literature values [38]. Gap filling for remaining powertrains using Euro-based emission values from HBEFA 4.1 database [35].	[35,38]
OECD Europe (Germany)	Based on the HBEFA 4.1 database	[35]
India	Based on the literature from [39] on vehicle stock based in New Delhi with estimates up to 2030.	[39]
Japan	Based on the literature for $PM_{2.5}$ and NO_x for diesel and gasoline vehicles for 2015 [36]. Extrapolation to future years based on ratios of emission factor trend development in Germany [35].	[35,40]
Eastern Europe (Russia)	EF weighting according to Euro-class fleet shares; Estimation of the composition of the vehicle fleet by Euro classe based on the literature and the time lag of the introduction of the Euro classes in Russia compared to that of Europe.	[35,41]
Africa (South Africa)	EF weighting according to Euro class fleet shares; Estimation of the composition of the vehicle fleet by Euro class based on the literature and the time lag of the introduction of the Euro classes in South Africa compared to that in Europe.	[35,42]
North America (the USA)	Based on the EMFAC2017 database	[43]

Germany

Emission factors for German passenger cars are obtained from the Emission factors for Road Transport Handbook (HBEFA). The emission factor values are differentiated according to the emission species (NO_x, $PM_{2.5}$), the calendar years (2015–2050), the drivetrain/fuel types (gasoline, diesel, CNG, G-HEV, D-HEV, G-PHEV, D-PHEV), the Euro classes (Pre-Euro until Euro 6) and the traffic situation/road type (urban, rural, motorway). For the weighting of the emission factors, Euro class stock shares are taken from HBEFA, drivetrain/fuel stock shares come from our own models (cf. Section 3.1) and traffic situation/road type shares are obtained from the project Transport and the Environment (VEU) [44].

Australia, Russia and South Africa

For the countries Australia, Russia and South Africa, no publicly available country-specific emission factor data sources are available. As, in these countries, the vehicle pollutant emissions are regulated based on the European standards, the base approach for obtaining stock-fleet average emission factors is the estimation of the composition of the gasoline and diesel vehicle stocks by Euro classes. This is based on information from the literature and/or the time lag of the introduction of the Euro standards in the respective country by Euro class, based passenger car stock composition and emission factors from Germany [35] as baseline. Figure 2 presents the resulting gasoline and diesel passenger car stock compositions according to Euro classes from 2015 to 2050 in Australia, Russia and South Africa.

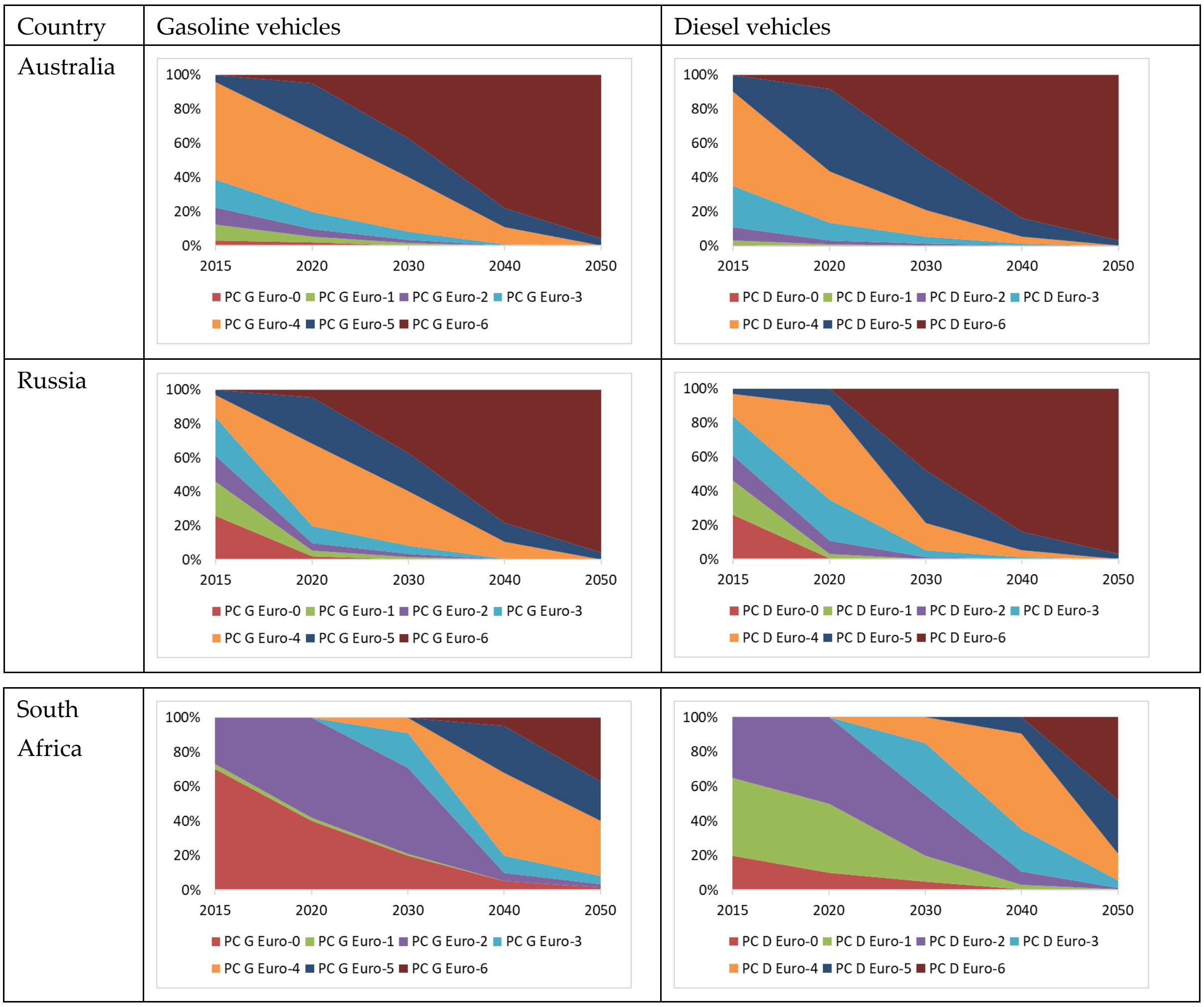


Figure 2. Gasoline and diesel passenger car stock compositions according to Euro classes from 2015 to 2050 in Australia, Russia and South Africa. The x-axis is the year, and the y-axis is the percentage of the vehicle stock fleet.

In Australia, Euro 5 and Euro 6 stages have been introduced via the Australian Design Rules (ADR) ADR79/03, ADR79/04, and ADR79/05. Full Euro 5 requirements were applied in November 2016, while the introduction of Euro 5 in the EU was in January 2010. Euro 6 came into effect in July 2018 in Australia, which corresponds to a delay of about 3.5 years compared to the original introduction date. Previous Euro stages were also introduced with a delay of approximately 5 years in Australia compared to the EU [45,46]. Based on these findings, Australia's petrol and diesel passenger car fleet compositions are estimated based on Germany's fleet compositions considering a delay of 5–10 years.

In Russia, the most recent emission standard adopted is Euro 5, which was implemented between 2014 and 2016. Based on information from the literature on the Russian passenger car stock composition in 2015 [41] and assuming a delay of 5–10 years between Russia's and Germany's fleet compositions, the development shown in Figure 2 is obtained.

In 2008, South Africa's petrol and diesel passenger car fleets mainly existed of Pre-Euro (or Euro 0 as displayed in Figure 2) and Euro 1 vehicles [42]. Euro 2 is the most recent emission standard, which was introduced between 2006 and 2008 [47]. Considering this information and additionally assuming a delay of approximately 20 years between the development of the passenger car stock of South Africa and Germany, South Africa's stock composition between 2015 and 2050 is estimated.

China

Mean $PM_{2.5}$ and NO_x emission factors for gasoline passenger cars in China, which constitute approximately 90% of the stock fleet in 2015 (cf. Section 3.1), are obtained from the literature [38]. The values are given for calendar years between 2015 and 2030. Values between 2030 and 2050 are extrapolated from these literature values based on fitted exponential curves. Emission factors for diesel and CNG vehicles are taken from Germany's HBEFA based values. As both drivetrains have neglectable stock fleet shares during the whole timeline, no significant bias is to be expected from this assumption.

Japan

Average $PM_{2.5}$ and NO_x emission factor values for Japanese gasoline and diesel passenger cars in 2015 are taken from Kurokawa and Ohara [40]. The yearly development of the average pollutant emission factors for the Japanese gasoline and diesel passenger car stock fleets is assumed to be similar to the corresponding development in Germany. Therefore, emission factor values for the remaining years are derived by applying Germany's gasoline and diesel vehicle-fleet-based pollutant emission factor development trends. Average CNG passenger car emission factors for Germany are applied.

India

Mean $PM_{2.5}$ and NO_x emission factors for gasoline, diesel and CNG passenger cars in the greater Delhi region based on Goel and Guttikunda [39] are considered as representative data for India. Emission factor values are given for the years 2012 and 2030. By linear interpolation, values for the years in between are obtained. Then, the emission factor development trend is extrapolated until 2050 based on fitted exponential curves. Though the methodology for extrapolation of emission factors of the power trains is not ideal in most cases, stock share and travel demand development plays a much more significant role in the final emissions in such countries.

Brazil

Country-specific $PM_{2.5}$ and NO_x emission factors for passenger cars fueled with gasoline, ethanol or various blending ratios of both fuels, with flex-fuel engines, can be found in the VEIN book as described from Ibarra-Espinosa et al. [37]. The Brazilian emission factors originate from the São Paulo Official Vehicular Emissions Inventory from the Environmental Agency of São Paulo State [36], which published the FTP-75 certification test results as an averaged database by type of vehicle and year. For this study, emission factors for vehicles registered in 1982 or before until registration year 2017 are considered. As the emission factors are available per registration year, the age distribution of the vehicle stock fleet is derived based on data of the estimate of the vehicle stock in 2017, which is also obtained from the Environmental Agency of São Paulo State [36]. Assuming that the oldest vehicles in use are 30 years old, fleet average emission factors per calendar year and fuel/drivetrain type can therefore be calculated. As a result, average emission factors until calendar year 2017 can be obtained for the following:

- passenger cars using gasoline blended with 25% ethanol;
- passenger cars with engines that use pure ethanol;
- passenger car with flex-fuel engines using gasoline blended with 25% of ethanol;
- passenger cars with flex-fuel engines that use pure ethanol.

In order to yield one average emission factor for passenger cars with gasoline engines, first, the flex-fuel emission factors are weighted by assuming a 50:50 share, as no further information on ethanol fuel shares of flex-fuel vehicles is available. Next, ethanol and flex-fuel vehicles are weighted according to their estimated stock fleet shares. Emission factors for two groups of gasoline engine vehicles are obtained, one with ethanol shares of 25% or less and one with higher ethanol shares. According to S&P Global Mobility statistical data on new vehicle registrations in Brazil, between 2016 and 2018, 95% of new vehicles were flex-fuel or ethanol vehicles, while 5% were (mainly) gasoline-fueled passenger cars [48]. As a simplified approach, these percentages are assumed as weighting factors in order to result in one average gasoline-fueled passenger car emission factor. The gasoline-fueled vehicle emission factors for the years between 2017 and 2050 are calculated by extrapolating the corresponding emission factor trends of the 2010–2017 timeframe. The mean emission factors for the diesel- and CNG-based drivetrains are used based on the data for the German vehicle stock fleet. As gasoline-based vehicles are predominant in Brazil's vehicle stock fleet throughout the considered timeframe, no significant bias is expected from this simplified assumption.

The USA

Emission factors for gasoline and diesel passenger cars were obtained from the EMFAC2017 web database [43]. EMFAC is a model that estimates the official emissions inventories of on-road vehicles in California. Besides total emissions, emission factors (or emission rates, as termed in the database) can be selected as data type. As region, "statewide" is chosen as the most comprehensive option. The years 2015, 2020, 2030, 2040 and 2050 are chosen as the base calendar years. Annual values are needed for all fuel types and aggregated values in terms of vehicle model years and speeds. After all selections are completed, the data can be computed and exported in .csv format. EMFAC provides emission factors for different activities or operating conditions. In this study, running exhaust emissions are considered, expressed in g/mile. The emission factors are then calculated per km. For CNG vehicles, which have <1% stock fleet share (Section 3.1), emission factors from Germany are applied.

Table A2 in Appendix D contains the considered $PM_{2.5}$ and NO_x emission factors for each studied country and drivetrain technology for the three base years 2015, 2030 and 2050.

2.1.4. Transport Demand

Emissions from transportation are strongly related to transport demand. Therefore, estimating the emissions up to 2050 is not possible without estimating the total number of km driven up to that year. For this analysis, we used the global passenger car travel demand estimated for each country. Our primary data are obtained from the study by Seum and Eisenmann [49], which we accessed during our project. Their study builds on the factors identified by Seum et al. [50], defining their data sources as follows: KC and Lutz [51] for population figures, Rob Dellink et al. [52] for economic development indicators, the European Commission [53] and OECD/ITF [54] for mobility statistics, TomTom [55] for the congestion index, the World Health Organization [56] for motorcycles and the IEA [57] for rail as well as national statistics, where available [49]. Figure 3 illustrates the global passenger car transport demand of the regions used in this analysis (the countries in each region can be seen in Appendix C). The graph shows that currently, most of the travel demand by cars comes from North America and Europe. However, in 2050, the role of these regions will be smaller with increasing demand from India and China. Therefore, an effective strategy to reduce the global emissions from passenger cars is only possible with developing countries involved.

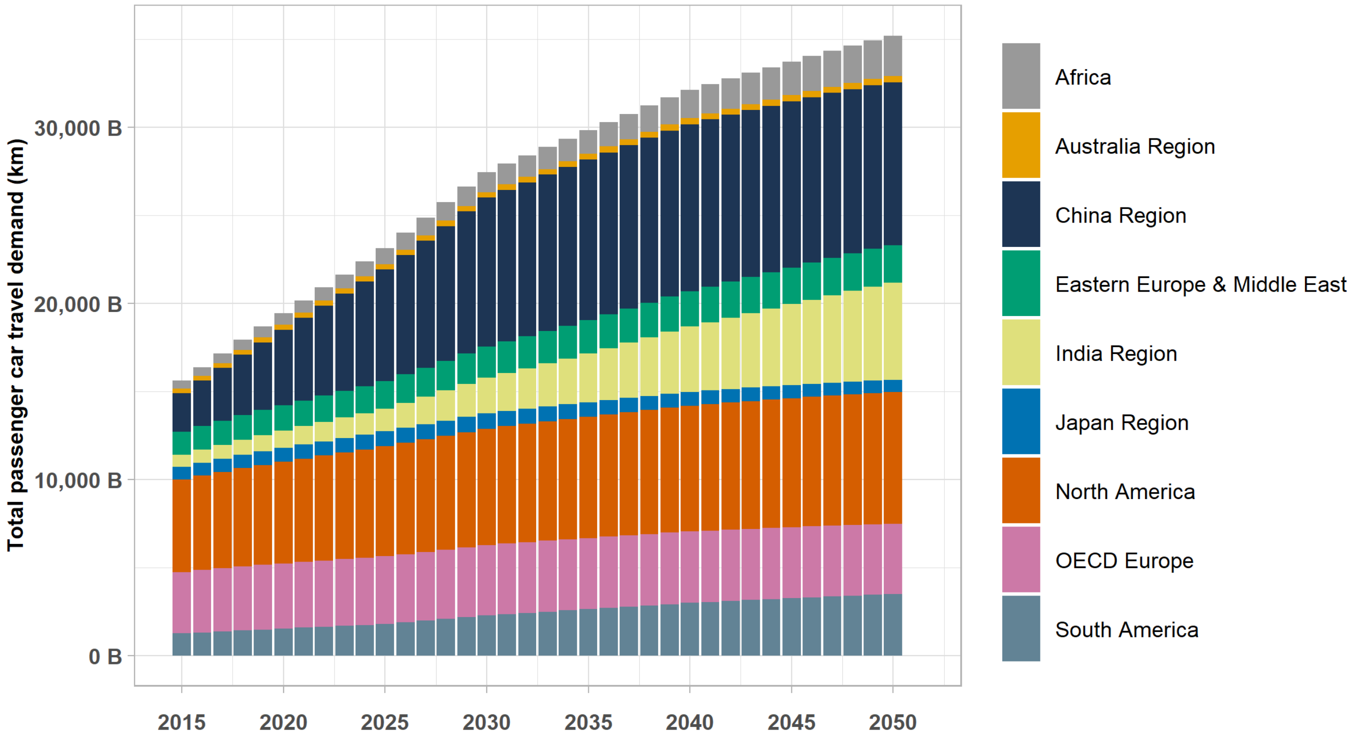


Figure 3. Development of the global passenger car transport demand [49].

In addition to the transportation demand, the powertrain and fuel types of the vehicles are also critical. Electrified vehicles emit significantly lower amounts of greenhouse gas and pollutant tailpipe emissions, if any. Also, gasoline and diesel vehicles can perform significantly differently depending on their emission class or age of use and the considered emission types. Therefore, to be able to analyze emissions from transportation in 2050, we estimated the shares of the different powertrains in the passenger transport demand in the future (Section 3.1). To estimate the travel demand for passenger cars with different powertrain options, we assume that the transport demand shares of powertrains will be based on the stock shares of these vehicles. Therefore, the future development of the travel behaviors of car owners from different powertrains is beyond this paper's scope.

In summary, we applied a bottom-up methodology, integrating a quantitative analysis with regional segmentation to capture diverse emission trends across varying powertrain technologies. Our approach combines global and country-specific analyses of three types of emissions (CO_2, NO_x and $PM_{2.5}$) at the country, regional and global levels. This method is replicable and offers insights that are applicable across multiple scales. However, it requires extensive data, necessitating some gap filling. We discuss these challenges in detail in the limitations section. The methodological framework of our study is illustrated in Figure 4.

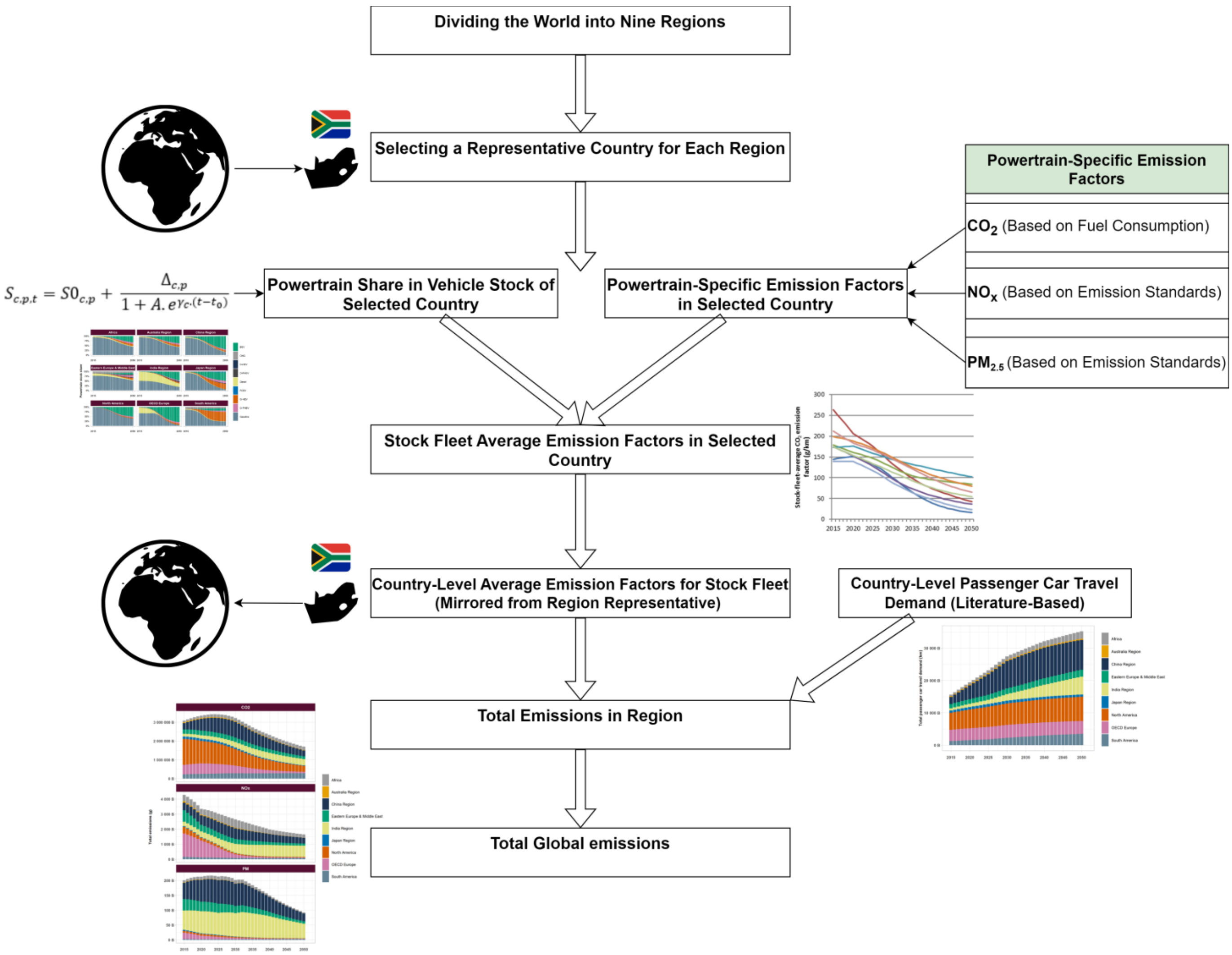


Figure 4. Methodological framework.

3. Results

3.1. Passenger Car Market Modelling

The results of the model can be seen in Figure 5. Our findings show that the OECD in Europe and China will continue to lead the electric car transformation. However, even in those countries, under the scenario that governments have ambitious EV targets and EV uptake is at the highest level, there will still be a small share of ICE vehicles left in 2050. Meanwhile, with the current regulations and announced government targets, South America, Eastern Europe and the Middle East, those represented by Brazil and Russia, respectively, will be the laggards. Because these countries are major energy suppliers in terms of ethanol (Brazil) and crude oil (Russia), it can be expected that the development of the passenger car market will depend strongly on the development of the energy supplies of these countries.

The graph illustrates the projected growth of electric cars in various countries and regions up to 2050. The data show that the OECD in Europe is expected to have the highest market share for electric vehicles, followed by China and North America. Notably, countries such as India, Japan, South Africa and Australia are projected to have comparable market shares, despite the differences in their income levels. In contrast, Eastern Europe, the Middle East and South America are found to have the smallest market shares. This disparity can be attributed to the fact that these regions possess economies that are heavily reliant on fossil fuels or alternate modes of transportation. This finding implies that the adoption of electric vehicles in these regions may be impacted by both economic and cultural factors.

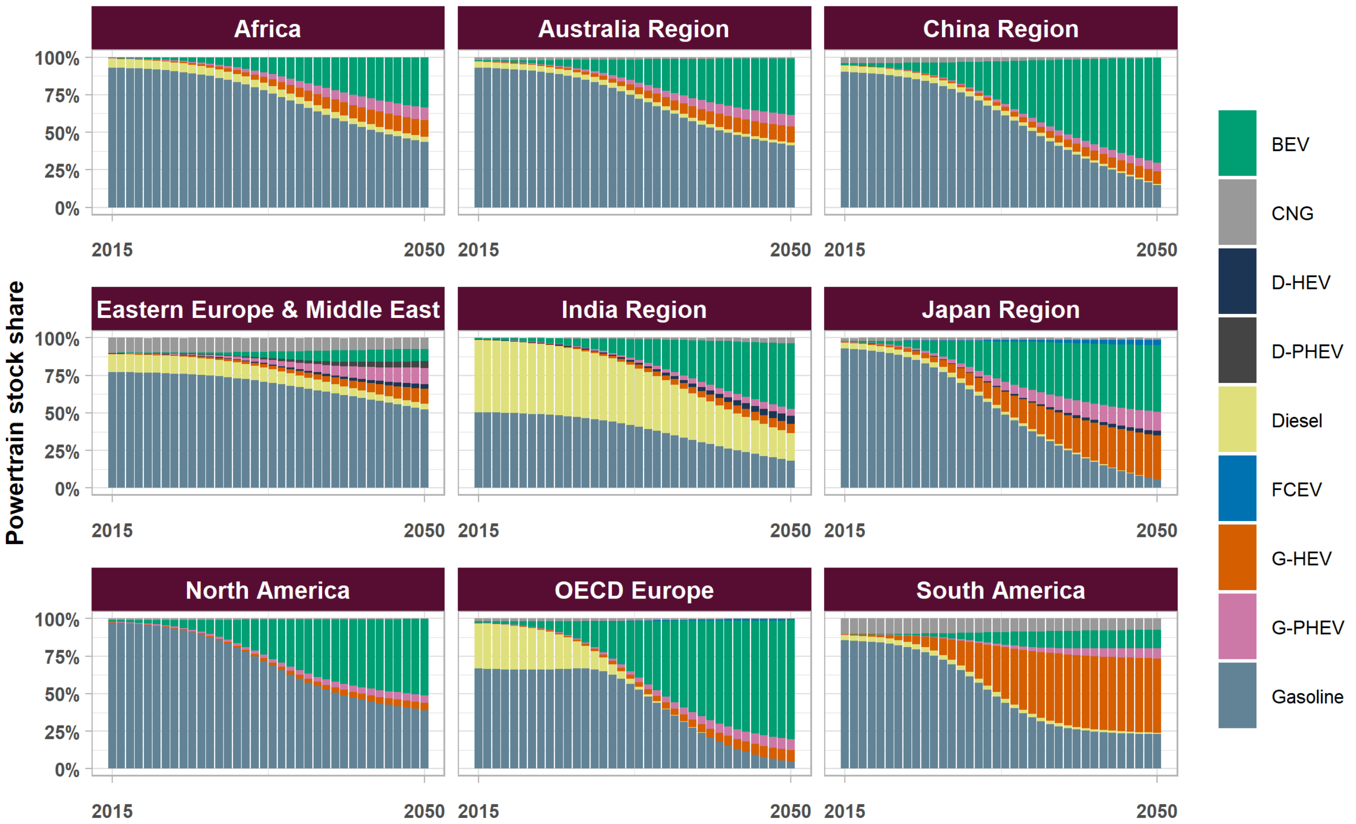


Figure 5. Drivetrain technology stock fleet share development until 2050.

To ensure the accuracy of our model and avoid any potential bias, we conducted a comparison of our results with various analyses from credible sources, as shown in Figure 6. Many sources share their results in terms of electric vehicles as plug-in hybrid electric vehicles and battery electric vehicles are counted together; thus, we used EV shares (BEV + G-PHEV) for our comparison. We compared our results for China, Germany, India, the USA and the world with those of the study of Rietmann et al. [12], in which 26 countries are analyzed, and two different scenarios from International Energy Agency projections [9]. As the OECD European values are based on Germany, we used the IEA's forecast for Europe for our comparison. In addition, we compared our results for Germany with the stock share forecast by Infras for the Handbook Emission Factors for Road Transport (HBEFA) [35]. Finally, we also add the global analysis from BloombergNEF to compare our findings for the world with their calculations [58]. Apart from India, our values are slightly lower than those of Rietmann et al.; however, in general, they are consistent with other studies, particularly for China, India and the world. It is worth noting that the results of Rietmann et al. [12] diverge from those of other analyses. This can be explained by the fact that the values in Rietmann et al. are estimated by the historical development of EV shares until 2018, while most of the other studies are more recent and mainly focus on a more extended time period in the future. For example, annual EV sales in India increased from 680 to 48.000 between 2019 and 2022 [9]. Therefore, the estimated values for India are lower in the study of Rietmann et al. [12] compared to the rest of the analyses. Additionally, our study found that the percentage of electric vehicles is slightly higher in Europe and the USA compared to that in the analysis conducted by the IEA and HBEFA. Our results aligned with our expectations as we considered the latest developments in the industry, such as the European ICE ban and the ZEV alliance of US states.

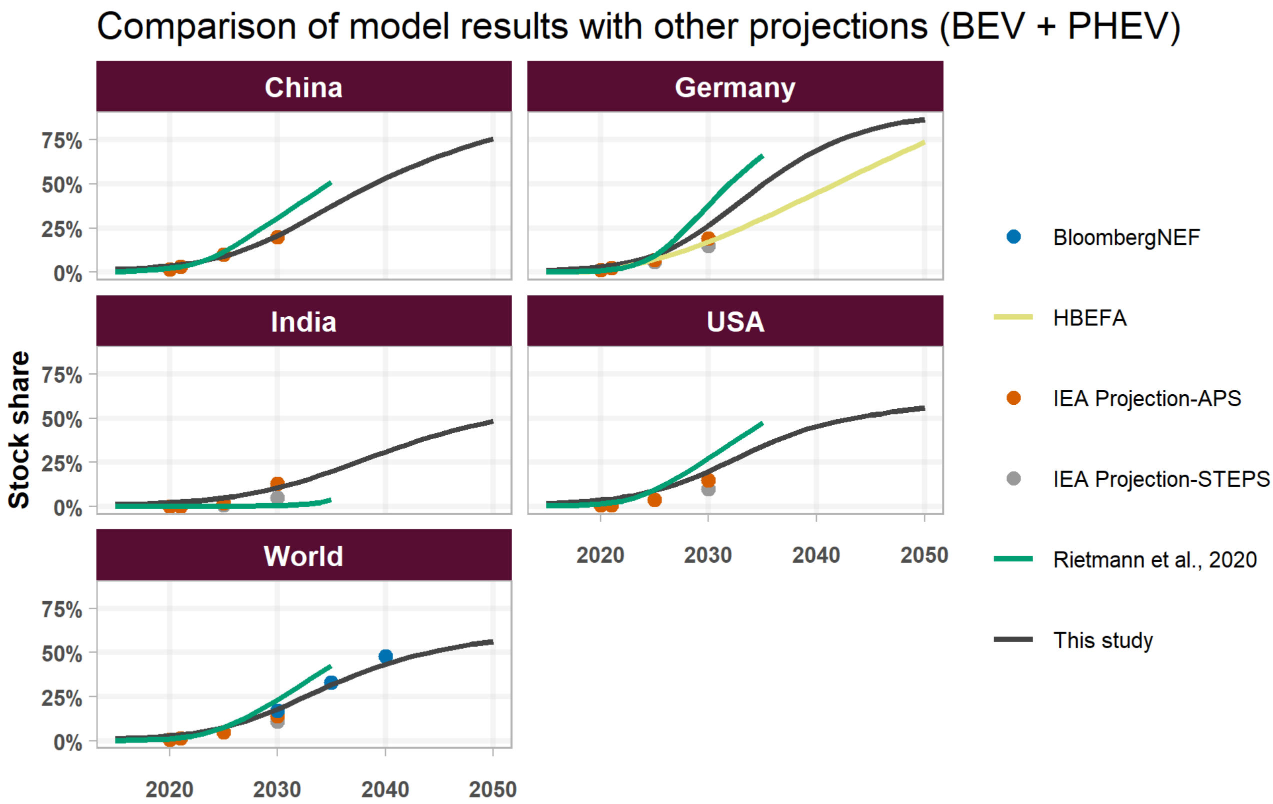


Figure 6. Comparison of the model with other EV stock share projections [9,12,35,58].

In addition to the studies shown in Figure 6, many other analyses project the future market share of electric vehicles on the road, largely aligning with the projections depicted in Figure 6. McKinsey, for instance, forecasts that one in every four passenger cars will be an electric vehicle by 2030 [59]. BCG, in an unconstrained scenario, similarly anticipates that one in every four passenger cars will be a battery-powered electric vehicle by 2035 [60]. However, not all studies concur with these optimistic projections. Kapustin and Grushevenko, analyzing both passenger cars and light commercial vehicles, estimated that electric vehicles might account for only 11% to 28% of the global fleet by 2040, which is substantially lower than most estimates, as shown in Figure 6 [61]. Adding another dimension, Jung et al. used three models to analyze the exponential adoption of BEVs, with their most conservative scenario predicting that BEVs will achieve a 31% share globally, which still surpasses many estimates, as shown in Figure 6 [62].

3.2. Overview of Global Emissions

Figure 7 presents the modelled development of global CO_2, NO_x and $PM_{2.5}$ emissions per world region and year. Global CO_2 emissions decrease from 3.1×10^9 t in 2015 to 1.7×10^9 t in 2050. Interestingly, global CO_2 emissions increase from 2015 to 2024, reaching a maximum level of approximately 3.4×10^9 t. Compared to the situation in 2015, global CO_2 emissions start to decrease as late as 2031. According to Figure 7, this increasing trend is mainly caused by China, whose CO_2 emissions increase greatly until end of the 2020s. Also, world regions like India, South America, Africa, Eastern Europe and the Middle East present continuously equal or even increasing CO_2 emission levels over the considered time frame from 2015 until 2050. While in 2015, North America was by far the main CO_2-producing world region, in 2050, its CO_2 figure is about the same as that for the world regions of India, China and South America. More details on how several CO_2 emission trends occur will follow in the country-based CO_2 emission analysis in Section 3.3 as well as in the discussion and conclusions sections (Sections 4 and 5).

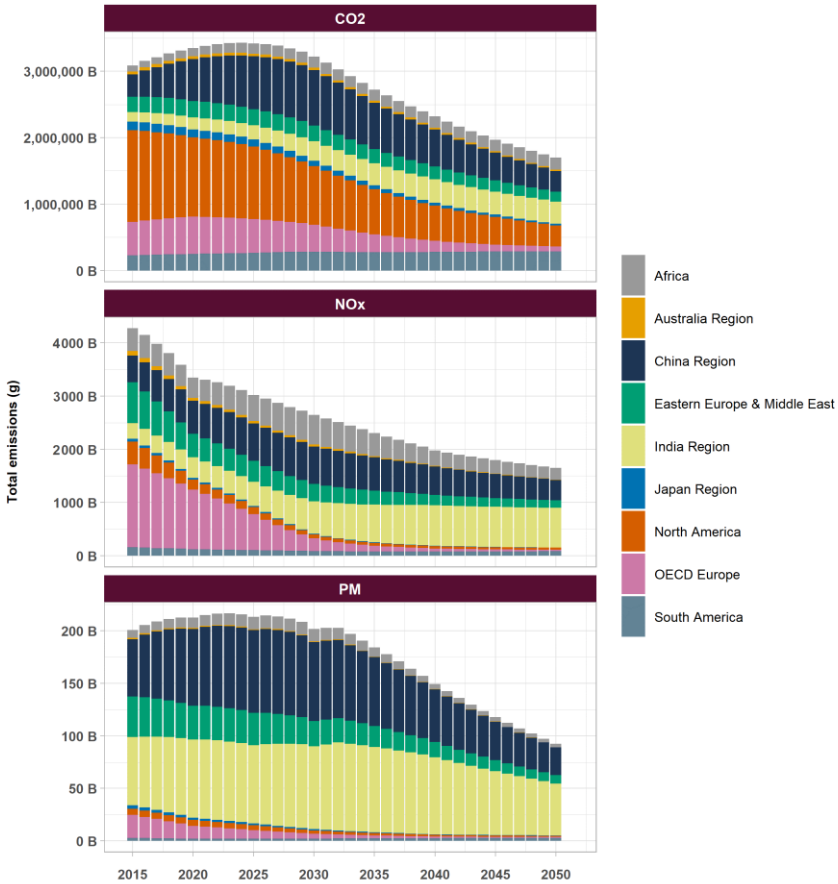


Figure 7. Development of the global CO_2, NO_x and $PM_{2.5}$ emissions by world region and year.

Global NO_x emissions significantly decrease from 4.3×10^6 t in 2015 to 1.6×10^6 t in 2050. This trend is highly influenced by the OECD European region, which is by far the main NO_x producer in 2015, while in 2050, its impact is barely visible because of a continuous and strong decrease. However, other world regions show different trends, especially India, whose NO_x levels increase during the considered timeline and which constitutes the main polluting world region in 2050. This statement is both relevant regarding NO_x and $PM_{2.5}$ emissions. For the latter, global emissions are mainly caused by India and China considering all years. The overall global trend looks similar to that in the case of CO_2. Worldwide $PM_{2.5}$ levels increase from 2015 (2.0×10^5 t) until 2026 (2.14×10^5 t) and the emissions fall below the 2015 level beginning in 2033. In 2050, global $PM_{2.5}$ emissions are modelled as 9.2×10^4 t. In Sections 3.4 and 4, we further analyze and discuss the mechanisms leading to the different pollutant emission trends in different world regions, especially focusing on India and China.

3.3. CO_2 Emissions per Country

Figure 8a shows the development of the stock fleet average CO_2 emission factors, and Figure 8b shows the total CO_2 emissions from 2015 to 2050 for the analyzed countries. The fleet average CO_2 emission factors show a decreasing trend from 2015 to 2050 for all countries. The USA is expected to have the strongest decline, being the largest emitter per km in 2015 and the sixth biggest emitter per km in 2050, cutting CO_2 emissions almost six-fold. Countries with emerging economies such as India, Brazil and South Africa show comparably high emission factors in 2015 and a constant but less steep decline compared to the USA until 2050. Regarding total passenger car CO_2 emissions, in 2015, the USA is by far the highest emitter due to the aforementioned high fleet average emission factor and also due to the high level of transport demand (cf. Figure 3). While transport demand in the US remains almost constant until 2050, as for most of the other countries or world regions, transport demand in India, China and South America increases significantly between 2015 and 2050. This leads to India being the highest CO_2 emitter in 2050, followed by the USA, Brazil and China as further major CO_2-producing countries. The example of China shows that a country with one of the lowest average per-vehicle emissions can be a major producer of total emissions, driven by its high transport demand. The strong increase in Chinese transport demand between 2015 and approximately 2030 directly translates to the shape of the CO_2 emission curve shown in Figure 8: there is a steep increase in emissions until 2027, while in the following years until 2050, emissions are decreasing as the transport demand stays at a constant level and the fleet average emission factors decrease sharply.

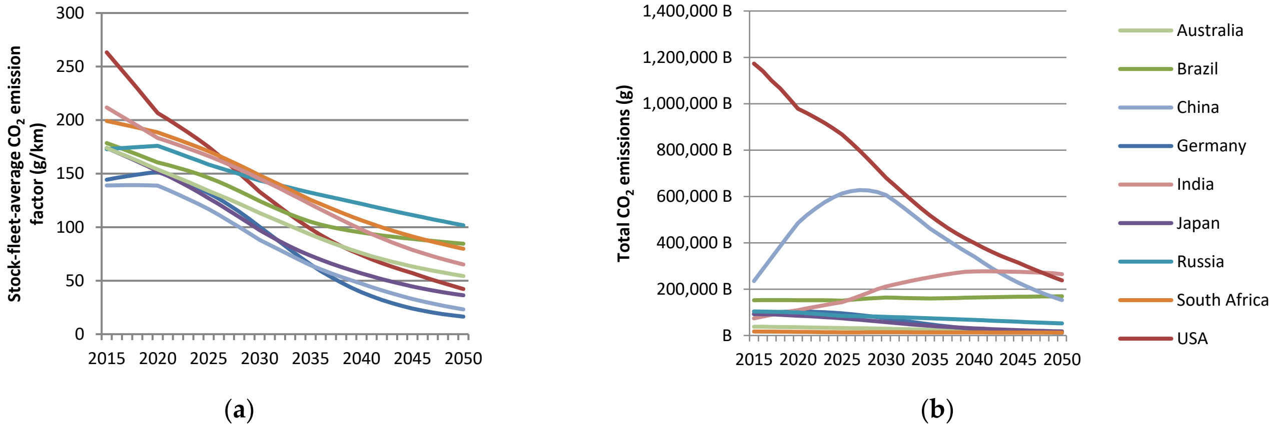
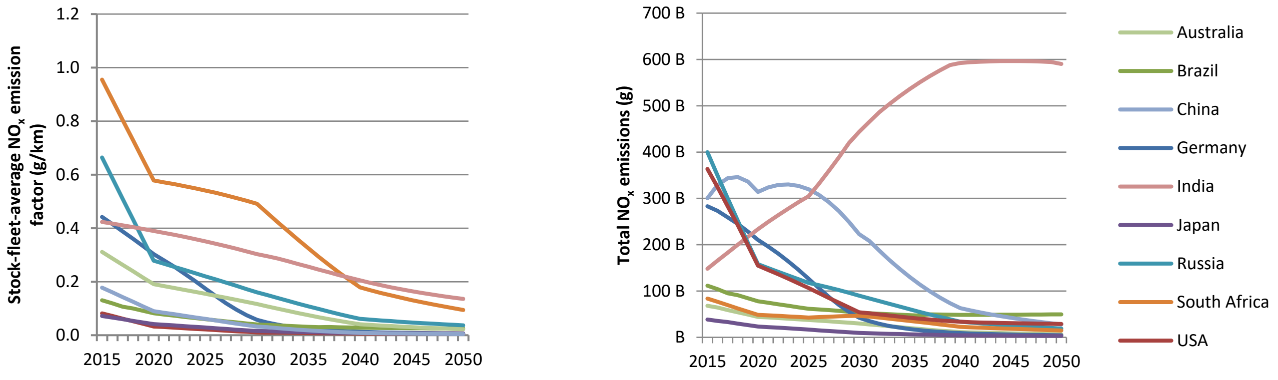


Figure 8. Development of the stock fleet average CO_2 emission factors (**a**) and the total CO_2 emissions (**b**) by country and year.

We expect the development of CO_2 emissions to be different for various countries or regions. We predict that CO_2 emissions in the USA and Europe (here Germany) decline constantly from 2015 to 2050, from 1173 million t CO_2/y to 238 million t CO_2/y in 2050 in the USA and from 92 million t CO_2/y to 11 million t CO_2/y in Germany. In China, our model shows a constant increase until approximately 2030, peaking in 2027, with 627 million t CO_2/y of overall emissions. Afterwards, CO_2 emissions are expected to decline rapidly to 153 t CO_2/y in 2050. In India, our model develops in the opposite direction, with increasing CO_2 emissions from 2015 (74 million t CO_2/y) to 2050 (265 million t CO_2/y). In Brazil, we predict a slight increase from 152 million t CO_2/y to 169 million t CO_2/y.

3.4. NO_x and $PM_{2.5}$ Emissions per Country

Figure 9a presents the development of the fleet average NO_x emission factors from 2015 to 2050 for each analyzed country. The trend shows a stepwise or constant decline in the average passenger car NO_x emissions for all countries. The highest values especially before 2030 are obtained for South Africa, Russia, Germany and India, which all have major diesel and/or old vehicle shares in their passenger car fleets, which is the main cause of their high per-vehicle NO_x emissions. The development of NO_x emissions decreases from 2015 to 2050 for all countries due to declining stock fleet average emission factors, except for India. Even though the stock fleet average NO_x emission factor is declining constantly in India, the transport demand increase is too dominant in order to limit emissions. In China, the trend is different to that in India, where NO_x emissions fluctuate between 2015 and 2023 due to the strong transport demand increase and the decreasing average vehicle emissions. Afterwards, during the time period until 2050, NO_x emissions continuously decrease due to very low average vehicle emissions.



(**a**) (**b**)

Figure 9. Development of the stock fleet average NO_x emission factors (**a**) and the total NO_x emissions (**b**) by country and year.

NO_x emissions are relatively high in Germany in comparison to the USA, considering their land area difference. This is mainly due to the share of diesel vehicles in the German passenger car fleet as opposed to the high share of gasoline-powered passenger cars in the United States, which are strictly regulated in terms of NO_x emissions. Interestingly, these conditions already change significantly by 2030, which demonstrates the impact of the strictly decreasing stock fleet average emission factors due to increasing BEV and decreasing diesel shares, as well as general fleet modernization by Euro 6 vehicles with more effective exhaust after-treatment systems. Therefore, in both countries, a severe decline in NO_x emissions is modeled. In Germany, the emissions decline from 283 thousand t NO_x/y in 2015 to 4.5 thousand t NO_x/y in 2050, which is a 63-fold decrease. In the USA, NO_x emissions decline from 364 thousand t NO_x/y to 29 thousand t NO_x/y in the same period. Similar to the USA and Germany, we also modeled a constant but less steep decline in NO_x emissions in China and in Brazil: in China, it decreased from 301 thousand t NO_x/y in 2015 to 28 thousand t NO_x/y in 2050, and in Brazil, it decreased from 112 thousand t NO_x/y to 50 thousand t NO_x/y. In India, the model predicts a constant increase in NO_x emissions, from 148 thousand t NO_x/y in 2015 to 590 thousand t NO_x/y in 2050.

Figure 10 shows the development of the stock fleet average $PM_{2.5}$ emission factors as well as the total $PM_{2.5}$ emissions from 2015 to 2050 for the analyzed countries. The stock fleet average $PM_{2.5}$ emission factors are predominantly high in India. South Africa and Russia's passenger car stocks also present higher emission factors than the rest of the analyzed countries, especially at the beginning. Even though India's stock fleet average $PM_{2.5}$ emissions decrease 10-fold from 2015 to 2050, this is still a difference of one order of magnitude to those of most of the other (predominantly industrialized) countries.

The development of $PM_{2.5}$ emissions is similar to the development of NO_x emissions; however, particularly high emissions occur in India, Southeast Asia (i.e., Thailand, Indonesia and Malaysia), Central Asia, the Middle East and the Arabian Peninsula. India is characterized by an early increase, caused by the transport demand increment peaking in 2033 at 62 thousand t PM/y and a later decrease down to 39 t PM/y in 2050, which is about the same level as that in 2017. A similar development can be observed in China with a peak of 15 thousand t PM/y in 2025 and a decrease to 2655 t PM/y in 2050. Compared to the case of India, China's transport demand increase slows down after 2030, so that the total particulate emissions are significantly reduced from the 2015 level until 2050. Apart from India and China, the countries investigated in depth show relatively low particular matter loads (Figure 10). The USA declines from 5000 t PM/y to 825 t PM/y from 2015 to 2050, and Germany decreases from 3895 t PM/y to 133 t PM/y in the same period.

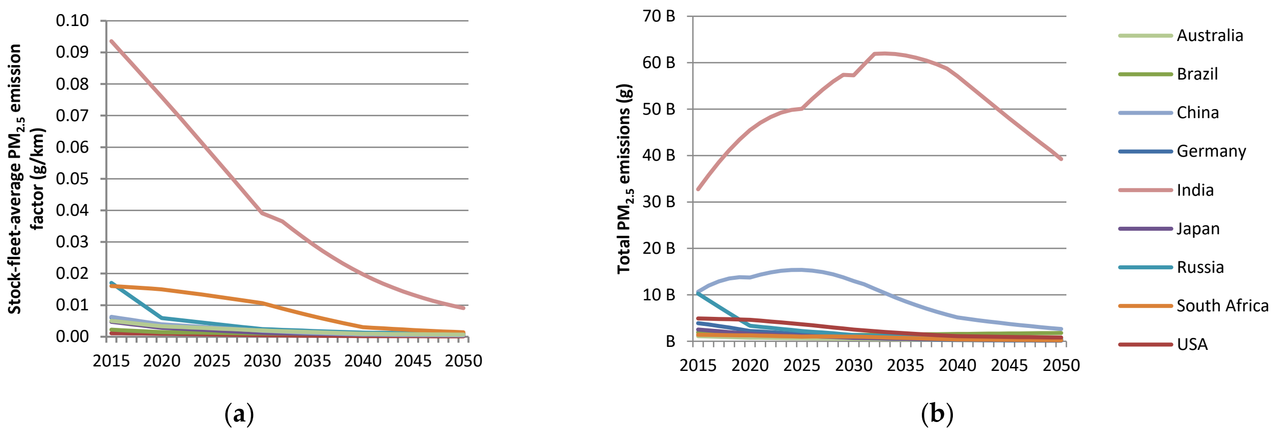


Figure 10. Development of the stock fleet average $PM_{2.5}$ emission factors (**a**) and the total $PM_{2.5}$ emissions (**b**) by country and year.

4. Discussion

CO_2 total emissions decrease in most of the analyzed countries, especially in the industrialized countries, like the US, Germany or Japan, whereas in India, China and Brazil, there is an increasing CO_2 emission trend mainly caused by the increasing transport demand in those developing countries. In China, the passenger car CO_2 emissions in 2015 increase 2.5-fold until 2027 before they decrease and reach the 2015 level again approximately in 2045. Indian passenger car CO_2 emissions keep increasing until after 2040 and stay at a high level until 2050, showing only marginally decreasing emissions. Brazil's passenger car CO_2 emissions show a flat and constant increase over the considered time frame. In addition to the increasing transport demand in South America over time, Brazil also has relatively low BEV stock shares, and therefore its stock fleet average CO_2 emission factors do not decrease as drastically compared to other countries with higher electrification rates. On the other hand, our modelling results show that South America's gasoline passenger car fleet will mainly be replaced by G-HEVs. This is due to the strong dependence of Brazil (and other Latin American countries) on ethanol as an energy carrier, so that it can be assumed that such regions are aiming for the hybridization of passenger car powertrains. It should be noted that for the CO_2 emissions calculation, this study only accounts for CO_2 originating from fossils, and therefore, the biogenic CO_2 from ethanol combustion is not considered in Brazil's CO_2 emission figures. This is a major difference to countries in Eastern Europe and the Middle East, where in 2050, half of their passenger car stock runs on fossil-fuel gasoline (Figure 5). Their dependence on fossil-fuel gasoline is disadvantageous regarding their stock average CO_2 emissions, which can be concluded from Russia's high figures (Figure 8). Due to the consistently relatively low transport demand in this world region, the effect on total CO_2 emissions is only marginal.

Regarding total NO_x and $PM_{2.5}$ emissions, all countries investigated besides India and China have a decreasing trend, and China's pollutant emissions start decreaseing from approximately 2025 onwards. In India, the results indicate that its NO_x emissions increase until 2045, and in the case of $PM_{2.5}$, its emissions increase until 2033. Pollutant emissions do not fall below their respective 2015 levels before 2050 in India. Thus, India seems to represent an exceptional case in terms of passenger car pollutant emission development. First, its stock average emission factors are high compared to those of most of the other analyzed countries. Even though India's passenger car stock fleet is assumed to have significant BEV shares, its high diesel shares persist over the considered time frame, which can be problematic in terms of NO_x and PM emissions. According to the literature, it can be assumed that before 2020, most of India's passenger car stock consisted of Bharat-Stage-IV-certified vehicles, which is equal to the Euro 4 standard [63,64]. For type approval or first registration, corresponding (diesel) vehicles are allowed to emit approximately three times more NO_x per km and about five times more PM/km compared to modern Euro 6 diesel passenger cars. Moreover, petrol and diesel fuel in India contain high sulfur levels, which can also be problematic regarding NO_x and PM emissions, as the high sulfur content affects the proper operation of the exhaust aftertreatment devices. like particulate filters or lean NO_x traps [39]. High emission factors can also be related to the existence of old, overloaded and insufficiently maintained vehicles in the stock fleet [64]. However, estimating the current average emissions of India's passenger car stock fleet is challenging, and its future development is highly uncertain. On the one hand, there is no recent national emission factor database covering all traffic situations for all vehicles, but only data from single-measurement campaigns covering specific driving situations or cycles and the vehicle types/technologies that are available. In this study, pollutant emission factors for India between 2015 and 2030 are estimated based on [39], and the respective pollutant emissions trends are extrapolated until 2050. However, the authors did not consider the introduction of new vehicle emission and fuel quality standards or their accompanying effects on fleet average emission factors. Therefore, the considered extrapolated trends up to 2050 might overestimate India's pollutant emissions from passenger cars in the future. Nevertheless, due to the assumed strong increase in transport demand in India, an increase in passenger car NO_x and $PM_{2.5}$ emissions seems likely, and policymakers should address this issue and its associated environmental and human health impacts.

Limitations and Uncertainties

Although this study can contribute to the literature from many different perspectives, it involves some uncertainties. Therefore, several limitations may have impacted our research outcomes. One of the limitations that may have affected our research results is the shares of alternative powertrains on the road in different world regions. Due to the broad scope we covered in this study, we were unable to conduct a detailed analysis of each aspect of the markets in the countries we studied. While we carefully designed our methodology to minimize potential biases and tried to validate our findings with those in the current literature, there were many variables that were not accounted for that could impact the development of alternative powertrains. We encourage future research to address these gaps to build a more robust model.

The considered data for transport demand from Seum and Eisenmann [49] were calculated based on observed data of average vehicle kilometers travelled per car within a region, and the estimations of car ownership were calculated from region-based curves as a function of GDP per capita. Apart from the inherent uncertainties in the development of GDP and population as well as their effect on car ownership, inputs relating to future changes in urban structure, congestion and thus travel demand per car, as well as increased investment in public transport were not considered in the model. Though it is difficult to incorporate and validate these in such global models, it is important to compare scenarios related to the development of travel demand given the direct impact it has on total emissions.

One of the main limitations regarding our emission estimations is the lack of specific and country-representative data for most of the considered countries, especially regarding emission factors and vehicle stock composition. Also, the limited number of countries that are analyzed in detail and the assumed clustering approach to cover the rest of the world's countries bring further uncertainty into the modelled emission figures. For our calculation of $PM_{2.5}$ emissions, we focus only on tailpipe emissions resulting from fuel combustion. While the results show a strong decline in global $PM_{2.5}$ emissions up to 2050, we did not cover non-exhaust particulate emissions originating from the abrasion of tires, brakes, roads and resuspension. As these particulate emissions are also caused directly from transportation and will become more significant if ICE vehicles are progressively replaced by EVs in the future, as shown in our model results, these need to be included in future passenger car or land transportation emission inventories. As already mentioned, though the methodology for the extrapolation of the country-specific emission factors of powertrains is not ideal in many countries, the development of their temporal stock share and travel demand plays a much more significant role in their final emissions. Interpolation and extrapolation performances are constrained by limited country-specific information, particularly in developing countries.

Due to the multiple sources of uncertainties within each input parameter for the bottom-up calculation chain of our emission estimations, an uncertainty assessment combined with a subsequent sensitivity analysis can be used to check the robustness of the results. While this goes beyond the scope of this paper, we recommend that future emission inventory compilers cover this.

5. Conclusions

Using a bottom-up model, this study analyzed CO_2, NO_x, and $PM_{2.5}$ emissions from passenger cars for different world regions up to 2050. The diffusion of alternative powertrains and emission factors of the vehicles on the road in the selected countries are examined to explore their emissions effectively. The created datasets (cf. data availability statement) which provide yearly emission values for each country globally can be useful especially for climate and air quality modelers.

The results of this study reveal that global passenger car CO_2, NO_x and $PM_{2.5}$ emissions decrease from 2015 until 2050 by approximately 45%, 63% and 54%, respectively. This is partly based on the fact that stock average passenger car CO_2, NO_x and $PM_{2.5}$ emissions per vehicle and kilometer driven decrease significantly in all world regions and analyzed countries. The main reasons for this trend are increasing electrification rates of the stock fleets, energy efficiency improvements, the introduction of stricter emission regulations and consequently the more advanced exhaust gas aftertreatment systems.

Emission trends vary by region, with CO_2 emissions decreasing in developed countries, like the USA, Germany and Japan, largely due to electrification. In contrast, developing countries, such as India, Brazil, and China, are experiencing increases in CO_2 emissions, driven primarily by growing transportation demands. In China, however, while there is an initial increase due to this demand, a subsequent reduction is observed as the fleet becomes more electrified. Regarding total NO_x and $PM_{2.5}$ emissions, a declining trend is observed in the representative countries, with reductions in China expected to begin by 2025. However, India continues to face increasing NO_x emissions up to 2045 and increasing $PM_{2.5}$ emissions up to 2033, with both pollutants not expected to fall below their 2015 levels until at least 2050. This persistent issue is attributed to India's continued reliance on diesel-powered vehicles and high-sulfur fuels, which significantly contribute to NO_x and $PM_{2.5}$ pollution, despite an increasing adoption of battery-powered electric vehicles. This study's findings indicate that although EVs are at the center of the discussions about the future of passenger cars, the progression of EV adoption varies significantly among different global regions. Our analysis found that while most passenger cars will be electric in China and Europe in 2050, the transformation will be slower in the rest of the world. Especially in countries like Brazil and Russia, where there is a strong connection between the domestic economy and the fuels used in their vehicles, this transformation will be slower under their current policies.

This study can be used as an inventory for future studies to fill the gap in the literature about global emissions in the future from passenger cars, especially for $PM_{2.5}$ and NO_x, and contribute a different approach for CO_2 emissions to the literature. Our findings offer insights into the direction of passenger car emissions and identify the key drivers behind these trends. Understanding this is crucial for policymakers, enabling them to target the most significant factors influencing emissions and to develop effective policies aimed at mitigating the environmental impact of increasing travel demand. Future research could build upon our findings by employing a clustering analysis based on market dynamics rather than geographical locations or by developing more detailed country-specific models. This approach could significantly improve strategies to reduce transportation emissions, providing a strong framework for policy development and environmental management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/futuretransp4020029/s1.

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Data Availability Statement: The passenger car CO_2, $PM_{2.5}$ and NO_x tailpipe emissions datasets generated in this study, which include values for each country globally and each year from 2015 to 2050, are available in Supplementary Materials.

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Details of Equation (1)

Equation (1):

$$S_{c,p,t} = S0_{c,p} + \frac{\Delta_{c,p}}{1 + A.e^{\gamma_c \cdot (t - t_0)}} \tag{A1}$$

Equation (1) is developed based on the general equation of S-curve logistic growth function [65].

$$y = \frac{k}{1 + b.e^{-\alpha.t}} \tag{A2}$$

We transformed the analysis by using the target values $\Delta_{c,p}$ that were mostly determined by government targets as k values in the general equation. Although our starting year was 2015 and the stock rates of the electric vehicles were negligible in most of the countries, we added $S0_{c,p}$ values to the equation to model both the already existing alternative powertrain options such as hybrid electric vehicles (HEVs) and policies focused on withdrawing ICE vehicles from circulation. In the generalized formula $-\alpha$ or γ represents the growth rate or steepness of the S-curve. Both for the γ and A values in the equation, we used the values of a previous study [15]. The γ values change for each country based on the year of the country's powertrain target. By setting γ as a function of the time gap between the target year and the starting year t_0, the shape of the curve can differ depending the target year. For the A values in the equation, we employed 100 since our target values were shares, not absolute numbers.

$$\gamma_c = -\frac{1}{\frac{t_\Delta - t_0}{10}} \tag{A3}$$

If the country only has a target for a single powertrain (for example, if the country has a target for only battery electric vehicles), all $S_{c,p,t}$ will be equal to $S0_{c,p}$ apart from the BEV. And the BEV share will increase as much as $\frac{\Delta_{c,p}}{1+A.e^{\gamma_c \cdot (t-t_0)}}$. Therefore, the total share will be more than one in the following years.

$$\sum_p S0_{c,p} = 1$$

$$\sum_p S_{c,p,t} = 1 + \frac{\Delta_{c,p}}{1 + A.e^{\gamma_c.(t-t_0)}}. \tag{A4}$$

To solve this problem, we updated the formula to that shown below to normalize the estimated market shares.

$$S_{c,p,t} \leftarrow \frac{S_{c,p,t}}{\sum_p S_{c,p,t}} \tag{A5}$$

Appendix B

Table A1. Biofuel energy consumption shares used in Equation (4).

Country	Fuel	Biofuel Rate (%)							
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Australia	Ethanol	0.006	0.003	0.001	0.001	0.0	0.0	0.0	0.0
	Biodiesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Brazil	Ethanol	15.0	14.0	14.0	15.0	15.0	14.0	14.0	14.0
	Biodiesel	1.0	1.5	2.0	2.5	2.5	3.0	3.0	3.0
China	Ethanol	1.1	4.6	12.5	18.6	20.5	20.9	21.0	21.0
	Biodiesel	1.0	4.4	11.9	17.7	19.5	19.9	20.0	20.0
Germany	Ethanol	4.4	5.1	6.3	7.6	8.4	8.8	8.9	9.0
	Biodiesel	4.0	4.3	5.1	7.0	8.4	8.9	9.0	9.0
India	Ethanol	0.3	0.6	1.0	1.2	1.5	1.7	1.8	2.0
	Biodiesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Japan	Ethanol	0.006	0.003	0.001	0.001	0.0	0.0	0.0	0.0
	Biodiesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Russia	Ethanol	0.015	0.007	0.004	0.002	0.001	0.0	0.0	0.0
	Biodiesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	Ethanol	0.009	0.005	0.2	0.3	0.3	0.4	0.5	0.6
	Biodiesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
USA	Ethanol	6.0	7.0	11.0	16.0	18.0	20.0	25.0	35.0
	Biodiesel	0.0	0.0	1.0	2.0	3.0	3.5	3.8	5.0

Appendix C. Country Clusters

Africa: Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Togo, Tunisia, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
Australia Region: Australia, New Zealand
China Region: Cambodia, China, Hong Kong Special Administrative Region, Macao Special Administrative Region, Democratic People's Republic of Korea, Fiji, French Polynesia, Guam, Haiti, Indonesia, Lao People's Democratic Republic, Malaysia, Mongolia, Myanmar, New Caledonia, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Vanuatu, Viet Nam

Eastern Europe & Middle East: Albania, Armenia, Azerbaijan, Bahrain, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Georgia, Iraq, Israel, Jordan, Kuwait, Latvia, Lebanon, Lithuania, Malta, Occupied Palestinian Territory, Oman, Qatar, Russian Federation, Saudi Arabia, Serbia, Syrian Arab Republic, The former Yugoslav Republic of Macedonia, Turkey, Ukraine, United Arab Emirates, Yemen
India Region: Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, India, Iran (Islamic Republic of), Kazakhstan, Kyrgyzstan, Maldives, Nepal, Pakistan, Sri Lanka, Tajikistan, Turkmenistan, Uzbekistan
Japan Region: Japan, Republic of Korea
North America: Canada, Mexico, United States of America
OECD Europe: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Republic of Moldova, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom of Great Britain and Northern Ireland
South America: Argentina, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Honduras, Jamaica, Martinique, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela (Bolivarian Republic of)

Appendix D

Table A2. Country- and drivetrain-specific $PM_{2.5}$ and NO_x emission factors in 2015, 2030 and 2050.

Country	Year	$PM_{2.5}$ EF (g/km)					NO_x EF (g/km)				
		G/G-HEV	D/D-HEV	CNG	G-PHEV	D-PHEV	G/G-HEV	D/D-HEV	CNG	G-PHEV	D-PHEV
Australia	2015	0.004	0.027	0.009	0.001	0.002	0.28	1.15	0.34	0.02	0.41
	2030	0.002	0.005	0.002	0.001	0.001	0.11	0.65	0.02	0.04	0.05
	2050	0.001	0.001	0.002	0.001	0.0003	0.04	0.11	0.02	0.02	0.05
Brazil	2015	0.001	0.012	0.009	0.0004	0.001	0.07	1.08	0.34	0.004	0.39
	2030	0.001	0.002	0.002	0.0004	0.0003	0.04	0.35	0.02	0.01	0.02
	2050	0.001	0.001	0.002	0.0004	0.0003	0.03	0.05	0.02	0.02	0.03
China	2015	0.006	0.012	0.009	0.002	0.001	0.13	1.08	0.34	0.01	0.39
	2030	0.002	0.002	0.002	0.001	0.0003	0.03	0.35	0.02	0.01	0.02
	2050	0.002	0.001	0.002	0.001	0.0003	0.01	0.05	0.02	0.01	0.03
Germany	2015	0.003	0.011	0.009	0.001	0.001	0.16	1.08	0.34	0.01	0.39
	2030	0.001	0.002	0.002	0.001	0.0003	0.05	0.35	0.02	0.02	0.02
	2050	0.001	0.001	0.002	0.001	0.0003	0.04	0.05	0.02	0.01	0.03
India	2015	0.045	0.15	0.014	0.016	0.012	0.22	0.65	0.17	0.01	0.23
	2030	0.022	0.067	0.006	0.008	0.012	0.10	0.59	0.05	0.03	0.04
	2050	0.009	0.028	0.002	0.004	0.015	0.04	0.52	0.01	0.02	0.26
Japan	2015	0.003	0.037	0.009	0.001	0.003	0.06	0.18	0.34	0.004	0.06
	2030	0.001	0.006	0.002	0.001	0.001	0.02	0.06	0.02	0.01	0.004
	2050	0.001	0.002	0.002	0.001	0.001	0.01	0.01	0.02	0.01	0.004
Russia	2015	0.007	0.052	0.009	0.002	0.007	0.65	1.06	0.34	0.04	0.38
	2030	0.002	0.005	0.002	0.001	0.001	0.11	0.65	0.02	0.04	0.05
	2050	0.001	0.001	0.002	0.001	0.0003	0.04	0.11	0.02	0.02	0.05
South Africa	2015	0.010	0.115	0.009	0.003	0.010	0.97	0.91	0.34	0.06	0.33
	2030	0.008	0.069	0.002	0.003	0.012	0.50	1.17	0.02	0.16	0.08
	2050	0.002	0.004	0.002	0.001	0.002	0.11	0.80	0.02	0.06	0.39
The USA	2015	0.001	0.015	0.009	0.0004	0.001	0.08	0.18	0.34	0.01	0.06
	2030	0.001	0.001	0.002	0.0002	0.0002	0.01	0.01	0.02	0.004	0.001
	2050	0.0003	0.0004	0.002	0.0001	0.0002	0.01	0.01	0.02	0.01	0.003

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